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ONTARIO GEOLOGICAL SURVEY

Open File Report 6041

Geology, Metamorphism and Geochemistry of Rocks of the Southern and Grenville Provinces in the Vicinity of the Grenville Front, Timmins Creek Area, near Sudbury, Ontario

by

E.I. Murphy

2001

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Foreword

As part of its commitment to training geoscientists for the future, in the early 1990s, the Ontario Geological Survey established a Mapping School Program whereby post-graduate university students could work in partnership with Ontario Geological Survey geoscientists on mapping-based thesis projects. Students benefit from this program through hands-on training in geological mapping techniques, and through the collection of field-based data that might not otherwise be obtained. In turn, the public benefits from this program through the collection of additional data that would not normally be done during the course of standard Ontario Geological Survey field projects, such as electron microprobe data and detailed petrographic studies. In addition, the public benefits by having a pool of skilled mappers available for work either the exploration industry or in government-supported mapping programs.

This document represents the final report resulting from one of these mapping school projects that was undertaken between the Ontario Geological Survey and the Department of Earth Sciences at Laurentian University between 1995-1999. The student, Elena Murphy, conducted detailed mapping and laboratory studies within a 4 km^2 area within Street Township, under the supervision of Professor R.S. James at Laurentian University, and Dr. R.M. Easton of the Ontario Geological Survey. This report represents a slightly edited version of the Master's thesis that was submitted, and successfully defended, by the student at Laurentian University in May 1999. The results of the Street Township mapping program, of which this thesis project is a part, are the subject of separate maps and reports released by the Ontario Geological Survey.

Abstract

The Timmins Creek area is located in Street Township, roughly 30 km east-northeast of Sudbury, Ontario. A 750 to 1000 m wide Transitional Zone of metasedimentary and metavolcanic schists occurs between the Southern Province (marked by the Ess Creek fault) and the Grenville Province (marked by the Grenville Front boundary fault). Structural, petrographic, metamorphic and geochronological data suggest that the boundary between these two provinces occurs at the Ess Creek fault, rather than the Grenville Front boundary fault. The former is marked by mylonites, the latter by hematitic, chlorite alteration and fault gouge. This places the Grenville Front 1 to 1.5 km further north than previously indicated in a 25 km long stretch between Timmins Creek and River Valley. This study shows that

1. the geology, geochemistry and geochronology indicate that the rocks forming the Transitional Zone can be correlated with units of the lower Huronian Supergroup;
2. fold patterns in the Grenville Province and Transitional Zone are similar to, but distinct from, those in the Southern Province;
3. mineral chemistry and whole rock geochemistry indicate that rocks in the Transitional Zone and Grenville Province domains have a similar origin and metamorphic history;
4. the presence of migmatites in the Grenville Province is the key feature that distinguishes Transitional Zone from Grenville Province rocks;
5. thermobarometry using a variety of calibrations, as well as TWEEQU and INVEQ, using staurolite-kyanite-garnet-biotite-muscovite bearing assemblages indicates conditions of 7 to 8 kbar and 630 to 680°C in the Transitional Zone and 8 to 9 kbar and 685 to 725°C in the Grenville Province. For the Southern Province, mineral parageneses indicate T ~350°C. Pressures are not well constrained, but are likely 2 to 5 kbar;
6. the estimated P–T–t path for the Timmins Creek area is clockwise;
7. best estimates of timing of partial melting and closure through 700°C are 995 ± 2 Ma from zircon (U/Pb) in folded leucosome of metagranites in the Grenville Province. U/Pb ages of metamorphic monazite from pelites in both Grenville Province and Transitional Zone domains give an age of 986 ± 3 Ma and represent closure through 700°C, confirming the suggestion that the Grenville Province and Transitional Zone had similar tectonic histories;
8. relatively rapid cooling in the Timmins Creek area is constrained between 995 to 990 Ma based on U/Pb zircon ages of folded and unfolded leucosome in the Grenville Province (average cooling rate = 7.5°C/m.y.). These data are comparable to the cooling histories along the Grenville Front in the Temagami and Killarney areas;
9. tectonic modeling suggests compression from the southeast resulted in the formation of an asymmetric structural and metamorphic antiform that can explain the present distribution of the metamorphic isograds across the Grenville Front and Grenville Front boundary fault in the Timmins Creek area.

Geology, Metamorphism, and Geochemistry of Rocks of the Southern and Grenville Provinces in the Vicinity of the Grenville Front, Timmins Creek Area, near Sudbury, Ontario

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Introduction

PURPOSE OF WORK

The study area straddles the boundary between the Paleoproterozoic Southern Province and Neoproterozoic Grenville Province east of Sudbury, Ontario (Figure 1). This boundary is commonly referred to as the Grenville Front or the Grenville Front boundary fault (Lumbers 1975). The Grenville Front represents a major metamorphic and structural discontinuity in the Precambrian crust. For at least a century, studies have been done on the rocks within the Grenville Front tectonic zone, which is a 40 to 50 km wide zone located immediately south of the Grenville Front. Although the geology of the Grenville Front tectonic zone has been relatively well documented at certain localities (Collins et al. 1930; Lumbers 1973, 1975, 1978; Dressler 1979; Davidson 1992, 1994, 1997, 1998; Davidson and Ketchum 1993), its detailed evolution in terms of deformation and metamorphism is still quite poorly understood. Furthermore, the protolith of the rocks immediately south of the Grenville Front is generally not known.

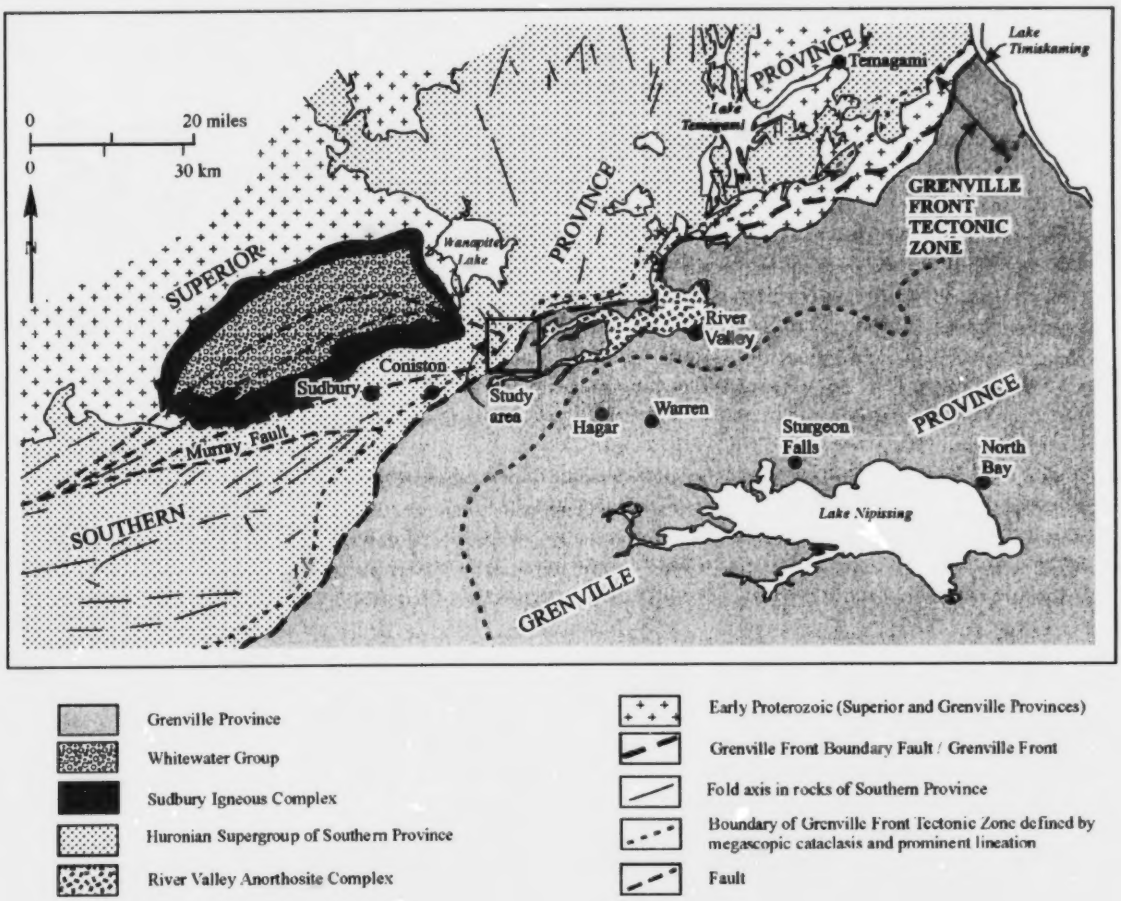

Figure 1. Geological map showing some major geological features in the vicinity of the Grenville Front tectonic zone in Ontario (modified after Lumbers 1978).

The study area is located in the northeast part of Street Township in the vicinity of Timmins Creek. The Ess Creek fault strikes northeast through the study area. Rocks north of the Ess Creek fault are recognizably lower Huronian Supergroup strata preserved at greenschist or subgreenschist metamorphic grade. The area 1 to 2 km south of the Ess Creek fault contains metavolcanic and metasedimentary rocks of medium amphibolite grade. Further to the south, these rocks grade into medium to upper amphibolite facies of typical Grenville gneisses. Lumbers (1975) placed the Grenville Front boundary fault along a late northeast-striking hematitic zone of shearing that separates schists from gneisses of similar metamorphic grade approximately 1 km south of, and parallel to, the Ess Creek fault.

The objectives of this study are

1. to determine the protolith(s) of the rocks that lie between the Ess Creek fault and the Grenville Front boundary fault as defined by Lumbers (1975);
2. to determine the metamorphic (*P–T* conditions) and tectonic history of the rocks referred to in (1);
3. to characterize the Huronian strata north of the Ess Creek fault and compare their geochemistry and metamorphic/tectonic history to the strata referred to above;
4. to examine the validity of the location of the Grenville Front (if defined as Southern–Grenville Province boundary) and suggest an alternate location, if appropriate.

PREVIOUS WORK

Considerable work has been done on the metamorphic rocks of the Grenville Front tectonic zone in the Sudbury area (e.g., Lumbers 1975) and there remain many areas where additional studies are needed. One such area is the Timmins Creek region in Street Township northeast of Sudbury. Early workers such as Collins (1913), Fairbairn (1939) and Lumbers (1973, 1975) described the geology within, and adjacent to, this area. Additional relevant studies in the Sudbury area have been done by Dalziel et al. (1969), Kwak (1968, 1971), La Tour (1979, 1981), Davidson (1992, 1994, 1997), and Fueten and Redmond (1992, 1997).

Collins (1913) mapped different assemblages of rocks in the northeast corner of Street Township, which is the area on which this research focusses. He described a strong, uniform schistosity in highly metamorphosed gneisses (Grenvillian) and granitic rocks. Granite bodies were interpreted to be younger than surrounding schists and gneisses. Coarsely recrystallized hornblende gneisses at the contact with the granite bodies are invaded along strike (070 to 080°) by bands of granite-pegmatite and quartz, which were interpreted to be derivatives of batholithic granites. Highly schistose, light grey formations, that are exposed along the CNR line in the northeast corner of Street Township, were described as a well-stratified, feldspathic quartzite (now recognized as Mississagi Formation quartzite).

Fairbairn (1939) mapped much of the same area as Collins (1913), and areas immediately adjacent. For several kilometres east and west of the hamlet of Crerar, and parallel to the CNR line, he mapped bands of "transitional" schists up to 1 km wide. On the north, they are bounded by gabbro (Nipissing gabbro) and Bruce Series conglomerate and, on the south, by pink and grey (Grenville Province) gneisses. Contacts between these schists and the Grenville Province gneisses were observed in two places, each marked by the development of very coarse sericite schist, which was interpreted as recrystallized fault zone material. Fairbairn (1939) subdivided the "transitional" schists (of Collins 1913) into a northern "quartz member", and a southern "biotite member", both of sedimentary origin. West and south of Ess Creek station, highly deformed granitic pebbles occur in the gneisses, supporting the sedimentary origin of these rocks. He agreed with Collins' (1913) and Quirke's (1930) conclusion that "the sedimentary portion of the gneisses represent metamorphosed and granitized Huronian sediments, in places

conglomeratic". On his map, Fairbairn (1939) shows the zone of "transitional" schists as being "undifferentiated" since they did not show features of the Cobalt or Bruce series (Huronian Strata).

Lumbers (1973) was the first to recognize intermediate to mafic volcanic rocks in the northeast corner of Street Township. He included these volcanic rocks in the Mississagi Formation of the Hough Lake Group of the Huronian Supergroup, even though they consist of schists and gneisses whose history is enigmatic. Unfortunately, Lumbers (1973) does not elaborate on why he assigned the volcanic rocks to the Mississagi Formation rather than correlating them with the Elliot Lake Group. In the study area, these rocks form the northern part of a package of metavolcanic and metasedimentary rocks that occurs as an east-trending band ~1 km wide between the Grenville Front boundary fault of Lumbers (1973) and the Ess Creek fault. This zone extends some 30 km eastward from Timmins Creek toward River Valley along the Sturgeon River valley (Figure 1). These are the rocks that Fairbairn (1939) classified as undifferentiated "transitional" schists. Thompson (1960) and Thompson and Card (1963) mapped a similar zone of "transitional" schists between the Ess Creek fault and the Grenville Front boundary fault, which they assigned to the pre-Huronian Sudbury Group. North of the Ess Creek fault metasedimentary rocks of the Mississagi and Bruce formations, intruded by Nipissing gabbro, are present (Thompson and Card 1963). The Ess Creek fault represents a zone of extensive mylonitization and may represent the eastward extension of the Wanapitei fault (Thompson and Card 1963; Easton et al. 1996).

Southwest of Street Township along the Grenville Front in the vicinity of Wanapitei, Coniston, and on the southeast shores of Richard–McFarlane–Long lakes, Dalziel et al. (1969) described structural relationships within rocks of both the Grenville and the Southern provinces adjacent to the Grenville Front. They observed that the rocks along the northwestern margin of the Grenville Province and the southeastern margin of the Southern Province have, in part, a common structural history. Some variation in rheological behaviour that they observed was thought to be related to differences in lithology and in metamorphic grade. This is the first report to attempt a correlation, based on structural and metamorphic history, between the Southern and Grenville provinces in the Sudbury area. This work led them to the conclusion that the main deformation, high-grade metamorphism and regional migmatization in the western part of the Grenville Province was probably Penokean in age.

Studies to evaluate *P–T* conditions of metamorphism immediately adjacent to the Grenville Front in the Sudbury area have been done by Kwak (1968, 1971) and La Tour (1981). The areas mapped by Kwak (1968, 1971) and La Tour (1979) had been previously mapped, in less detail, by Grant et al. (1962). Kwak (1968, 1971) mapped a series of mineral isograds southeastward from the Grenville Front. From northwest to southeast, these are: staurolite-quartz, kyanite-muscovite and sillimanite-potassium feldspar. These isograds correspond to a progressive metamorphic change increasing with distance into the Grenville Province. Kwak (1971) used the mineral assemblage data to show that the *P–T* conditions, in the Grenville Province south of Sudbury, varied from 670°C and 6.3 kbar to 750°C and 7.3 kbar. La Tour (1979) mapped similar staurolite and sillimanite isograds, however, he found that the isograds coincided with two discrete mylonite zones (MZI and MZII). The staurolite isograd lies in the middle of MZI (but does lie on the trace of the Grenville Front boundary fault), whereas the sillimanite isograd lies along the western boundary of MZII. From *P–T* studies, La Tour (1981) proposed that MZII developed during prograde metamorphism and MZI during retrograde metamorphism, therefore MZII is probably older than MZI. Garnet-biotite geothermometry by La Tour (1981) yielded temperatures of ~540°C for staurolite-grade rocks and ~610°C for sillimanite-grade rocks. Assuming a geothermal gradient of ~21 to 24°C/km and the fact that sillimanite-bearing rocks at Baby Lake must be proximal to the kyanite stability field, La Tour (1981) estimated that 1) rocks in the area formed at ~5.75 kbar, and (2) significant south over north displacement occurred within the mylonite zone separating the staurolite and sillimanite zone rocks.

Various aspects of the structure, metamorphism and tectonics of the rocks along the Grenville Front in the study area have been discussed by Davidson (1992, 1994, 1998) and Davidson and Ketchum (1993). Most notably, these authors describe the relationship between faults in the Southern Province and the Grenville Front southeast of Sudbury with determination of displacement along these faults and their relative ages (Davidson 1992, 1994). Davidson and Ketchum (1993) also discussed the correlation of Huronian stratigraphy and Nipissing gabbro across the Grenville Front. Davidson's (1998) observations on folding within the Grenville Province are similar to those reported herein.

A major study of the metamorphic history of the Southern Province has been done by Card (1964, 1978). He has shown that metamorphism in the Southern Province consists of "high temperature nodes superimposed on a lower or intermediate grade background". The "nodes" belong to the lower amphibolite facies, where staurolite and andalusite exist, whereas the "background" is low to middle greenschist facies.

Structural studies by Fueten and Redmond (1997) in the area immediately south of Sudbury show significant ductile, south-over-north, reverse faulting along the newly documented Long Lake fault, which is likely part of the Murray fault system. As a result, a tectonically transported lower stratigraphic section of the Huronian Supergroup, which underwent conditions of relatively higher metamorphism (staurolite-, andalusite-bearing metapelites) became juxtaposed against low-grade metamorphic rocks. They suggested that the major movements along this fault were coincident with 1453 to 1445 Ma deformation in the region and with the minor effects of the Grenville Orogeny at circa 1000 Ma.

PRESENT STUDY

This project describes the results of a Master's of Science thesis project undertaken by the author as part of the Laurentian University–Ontario Geological Survey Mapping School program. This joint program is designed to encourage mapping-based research projects within Ontario, both to give students mapping experience and to allow for research beyond the scope of normal Ontario Geological Survey mapping projects. In this instance, the thesis project was conducted in conjunction with a 1:20 000 scale mapping project of Street Township, east of Sudbury, Ontario. It represents a detailed study of a small portion of Street Township where key geologic and metamorphic relationships are exposed.

Reconnaissance field work and preliminary geochemical and petrographic sampling was conducted by the author and R.M. Easton of the Ontario Geological Survey in October 1995. Mapping of Street Township was conducted by the author, with the assistance of Sue Buckley, in conjunction with mapping by R.M. Easton, during the period June to August 1996. Sampling for U/Pb geochronology of selected rocks within Street Township, including the thesis area, was conducted by Fernando Corfu (Royal Ontario Museum) and R.M. Easton in September 1996.

The area for the thesis study was selected in July 1996, and was mapped and sampled by the author over a four-week period during August to October 1996. An additional three weeks of work was conducted by the author and Dr. Richard James (Laurentian University) in the thesis area during the period August to September 1997. Mineral chemistry studies were conducted by the author during the period December to May 1997 using the microprobe facilities at the Geoscience Laboratories, Willet Green Miller Centre, Ministry of Northern Development and Mines. Geochemical analyses of samples from Street Township and the study area were also done at the Geoscience Laboratories. The author did not conduct the geochemical work because the main emphasis of the thesis was on the geologic and metamorphic history of the area.

Preliminary results of the mapping of Street Township were reported by Easton et al. (1996) and Easton (1996) in the Ontario Geological Survey *Summary of Field Work and Other Activities 1996* volume. Buckley et al. (1997) presented preliminary results on metamorphic conditions in Street Township. Easton and James (1997a, 1997b, 1997c) presented a preliminary analysis of the geochemistry of mafic gneisses and paragneisses from Dill, Dryden and Street townships. Geochronology results from the area are described in Corfu and Easton (1998, in press) and Corfu et al. (1998), and are summarized in this report. A coloured geological map of Street Township was released in 2000, after completion of the thesis (Easton and Murphy 2000).

Due to the fact that this thesis was part of the mapping school program, it was necessary to publish or present some of the results of this thesis in a preliminary form to meet the requirements of the program. In some instances, the author is not listed as the senior author since these preliminary publications were the result of a team effort. Publications directly related to this thesis, in which the author made a major or significant contribution include Easton et al. (1996), Buckley et al. (1997), Murphy et al. (1998, 1999) and Corfu et al. (1998). In addition, Davidson et al. (1999) includes a description for a one-day field trip, which visits many key outcrops in the area. These six aforementioned publications constitute part of this thesis project.

DEFINITIONS

The following terms are defined below in terms of their usage in the thesis. This is done in order to prevent confusion on the part of the reader.

Grenville Front: Ostensibly, the Grenville Front is the boundary between the Grenville and Southern provinces. Rocks to the north and west of the Grenville Front belong to the Southern or Superior provinces, whereas rocks to the south and east are part of the Grenville Province. How this boundary is defined is a subject of debate; in some areas, it is a metamorphic change, in other areas it is a change in structural style and orientation, in others it is a change in lithology. In Ontario, the Grenville Front is commonly marked by faults, locally of more than one age (*see* "Grenville Front boundary fault").

Grenville Front boundary fault: The Grenville Front in Ontario is typically marked by a fault, which separates lower grade rocks of the Southern Province from higher grade rocks of the Grenville Province. This fault has been termed the Grenville Front boundary fault (Ayres et al. 1971; Lumbers 1973, 1975). The fault is commonly marked by a zone of hematized and chloritized fault gouge.

Grenville Front tectonic zone: Lumbers (1971) defined this zone as the northwest margin of the Grenville Province consisting of rocks which exhibit a northeast-trending foliation and southeast-plunging lineation within the gneissic rocks of the Grenville Province and adjacent Southern and Superior provinces. Current usage of the term generally restricts the definition to rocks with a strong Grenville imprint.

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assistance in the editing of this thesis are greatly acknowledged. I wish to extend my thanks to Dr. Robert Whitehead for his help in the final preparation of my presentation.

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Regional Geological Overview

SOUTHERN PROVINCE

Introduction

The Southern Province in Ontario stretches from Sault Ste. Marie east to Sudbury and northeast to the Ottawa River and Cobalt (Bennett et al. 1991). It consists of Paleoproterozoic metasedimentary and metavolcanic rocks of the Huronian Supergroup, mafic intrusions of the East Bull Lake intrusive suite, Nipissing gabbro suite and the Sudbury Igneous Complex, and the Whitewater Group. Also included in the Southern Province are Mesoproterozoic plutonic and minor volcanic rocks of the Killarney Magmatic Belt. The latter belt of rocks is cut by the Grenville Front, so that these rocks occur in both the Southern and Grenville provinces (cf. Easton 1992). Also present in the Southern Province are anorogenic plutonic rocks emplaced between 1.5 and 1.45 Ga, and the 1.24 Ga Sudbury diabase dike swarm (Krogh et al. 1988; Bethune 1997).

The Huronian Supergroup (Figure 2) was deposited unconformably on 2.8 to 2.5 billion year old Archean plutonic and supracrustal rocks of the Superior Province. Locally, a paleoweathering surface is preserved at the unconformity, particularly in the Thessalon and Elliot Lake areas (Bennett et al. 1991). The age of the Huronian deposition is constrained between 2.45 Ga, the minimum age of the Copper Cliff rhyolite and the coeval 2.477 Ga Murray granite (Krogh et al. 1984, 1996), and 2.2 to 2.02 Ga, the age of the Nipissing gabbro suite (Corfu and Andrews 1986; Noble and Lightfoot 1992).

The Huronian Supergroup can be subdivided into four groups (Figure 2): the Elliot Lake, Hough Lake, Quirke Lake and Cobalt groups. The lowest unit, the Elliot Lake Group, consists of both metasedimentary and metavolcanic rocks. In the Sault Ste. Marie area, the lowest unit is the arkosic Livingstone Creek Formation, which is overlain by mafic and felsic volcanic rocks of the Thessalon Formation. Mafic rocks of the Thessalon Formation are continental tholeiites (Jolly 1987; Tomlinson 1996). In contrast, in the Sudbury area, the volcanic units are thicker, contain more felsic members, and lie beneath the sedimentary rocks (Bennett et al. 1991). Three main volcanic units are present in the

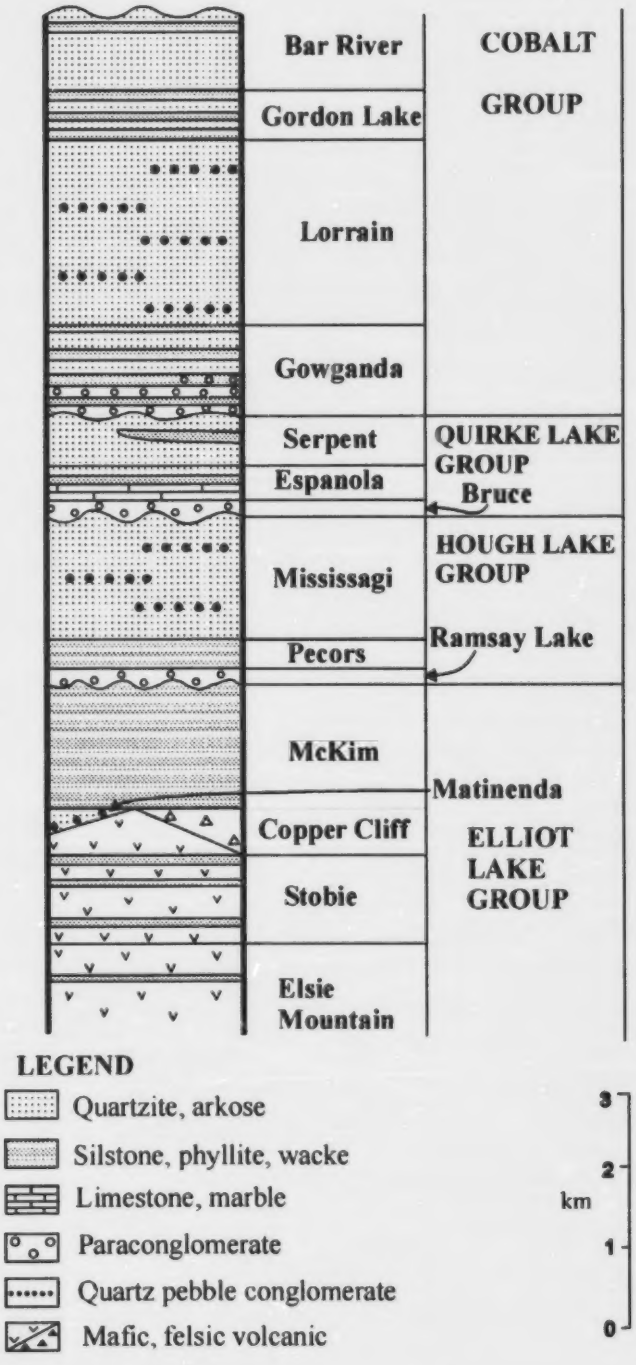


Figure 2. Stratigraphy of the Huronian Supergroup in the southeastern Southern Province (*after* Roscoe and Card 1993).

Sudbury area: 1) tholeiitic basalts of the Elsie Mountain Formation, 2) more evolved tholeiitic basalts, dacites, and metasedimentary rocks of the Stobie Formation, and 3) dacites and rhyolites of the Copper Cliff Formation, which are likely coeval with the Murray and Creighton granites. These units interfinger with, and are overlain by, the Matinenda Formation in the west and McKim Formation in the east (Bennett et al. 1991). Volcanic rocks of the Thessalon Formation have received greater study, particularly their geochemistry (Tomlinson 1996), than have the volcanic rocks of the Sudbury area.

Several layered mafic intrusions occur at the base of the Huronian Supergroup in the Elliot Lake, Agnew Lake and Sudbury area; they are referred to as the East Bull Lake intrusive suite. These bodies have been described most recently by Peck et al. (1995) and Vogel (1996) and dated at 2.491 to 2.475 Ga (Krogh et al. 1984; L.M. Heaman, University of Alberta, personal communication, 1998), and, in most instances, appear to be slightly older than the volcanic rocks of the Elliot Lake Group.

The three groups overlying the Elliot Lake Group (Figure 2) consist of three sedimentary cycles of conglomerate, mudstone, siltstone or carbonate, capped by cross-bedded sandstone (Bennett et al. 1991). These three sedimentary groups have been best studied in the Elliot Lake–Espanola area (see references *in* Bennett et al. 1991). Conglomerate units (Ramsey Lake, Bruce and Gowganda formations) in each of the cycles have been interpreted as being glaciogenic in origin (e.g., Junnila and Young 1995; Fralick and Miall 1989), likely deposited in a marine environment adjacent to an ice shelf. The siltstone and sandstone units are interpreted to represent deposition during warmer intraglacial or postglacial periods in either fluvial or marine environments (e.g., Junnila and Young 1995; Fralick and Miall 1989). Part of the evidence for climatic regimes is geochemically based (e.g., Nesbitt and Young 1982; Fedo et al. 1997), with the glaciogenic units having a higher percentage of unweathered rock debris compared to the units deposited in the post-glacial intervals.

The Huronian Supergroup is interpreted to represent a Wilson cycle, starting from a rifting phase represented by Elliot Lake, Hough Lake and Quirke Lake groups, followed by a "passive" margin sequence (Cobalt Group), and final closure due to a continent–arc collision between the Superior–Southern provinces and the Wisconsin Magmatic Arc Terrain (e.g., Young 1983; Hoffman 1989; Bennett et al. 1991). This collision event, at circa 1.89 to 1.85 Ga, is believed to be responsible for most of the metamorphism and deformation present within the Huronian Supergroup and is generally correlated with the Penokean event whose type locality is in the area south of Lake Superior. The tectonic setting responsible for intrusion of the Nipissing suite intrusions at circa 2.2 Ga is unknown, but the earliest phases of Penokean deformation (Blezardian) preceded this event.

Riller et al. (1999) take a different view, and have suggested that much of the deformation and metamorphism in the Southern Province occurred during the Belzardian orogeny (between 2.45 and 2.0 Ga), with a subsequent deformation pulse occurring during the Penokean. Without reliable U/Pb ages that directly constrain the age of metamorphism and deformation affecting the Huronian Supergroup, it is not possible to determine the validity of the suggestion made by Riller et al. (1999).

Of major economic importance is the 1.85 Ga Sudbury Igneous Complex (e.g., Naldrett et al. 1984), which consists of a lower noritic portion and an upper granophyric portion. These rock units outline a synclinorial basin occupied by pyroclastic (Onaping Formation) and sedimentary rocks (Onwatin and Chelmsford formations) of the Proterozoic Whitewater Group (Rousell 1984). Associated with the Sudbury Structure are series of brecciated rocks, termed the Sudbury breccias (Rousell 1984). These breccias consist of randomly oriented blocks of country rock in a fine-grained, pseudotachylite matrix. The breccias occur up to 100 km from the Sudbury Igneous Complex, but are most abundant adjacent to it. To date, metamorphosed equivalents of these breccias have not been identified within the Grenville Province. Reflection seismic imaging reveals that the Sudbury Structure is remarkably asymmetrical at depth (Wu et al. 1995); a clearly defined, major, northeast-striking imbricated fault zone is apparent in the

seismic data and establishes that thrust faulting played an important role in northwest-southeast shortening of the Sudbury Structure.

Following the Sudbury event at 1.85 Ga (Krogh et al. 1984), the southern part of the Sudbury Structure was weakly metamorphosed, an event which also retrograded previously metamorphosed rocks of the Huronian Supergroup. In the Sudbury area, a sodium metasomatic event at circa 1.7 Ga locally altered rocks of the Huronian Supergroup (Schandl et al. 1994). The alteration pattern is most apparent in northeast-striking fault breccias that are commonly gold bearing. It is not known if this metasomatism is linked to events in the Killarney Magmatic Belt which formed at 1.75 to 1.73 Ga. Felsic plutonism occurred at 1.5 to 1.45 Ga in the Southern Province and the Killarney Magmatic Belt. In the latter area, and in the Grenville Province, this event is associated with deformation and metamorphism (e.g., Bethune 1997).

In summary, the main tectonic events affecting the Southern Province area are rifting, volcanism, and continental margin sedimentation between 2.5 and 2.2 Ga; mafic magmatism at 2.2 Ga, the Penokean orogeny at 1.89 to 1.85 Ga, the Sudbury event at 1.85 Ga, localized retrograde metamorphism between 1.85 and 1.7 Ga, plutonism related to the Killarney Magmatic Belt at 1.75 Ga, localized sodium metasomatism at 1.7 Ga, felsic plutonism (and possible localized deformation) at 1.45 Ga, continental extension and mafic dike emplacement at 1.24 Ga, and localized effects of the Grenville orogeny at 1.0 Ga.

Geology of the Southern Province in the Sudbury Area

Card et al. (1977) and Debicki (1990) have summarized the geology of the Huronian Supergroup in the Sudbury area. They documented the areal distribution of Huronian Supergroup formations, but no complete section is present in any one area. Their best estimate of the total thickness of the Huronian Supergroup strata in the Sudbury area is 9300 m, including the Elliot Lake Group (2850 m), the Hough Lake Group (3750 m), the Quirke Lake Group (2500 m) and the Cobalt Group (1250 m).

Similar studies were done by Dressler (1982) whose data shows a considerable thinning of the Huronian Supergroup strata north and northeast of Sudbury. Total thickness of the Huronian Supergroup immediately west of Wanapitei Lake is 5250 m, whereas the Elliot Lake Group alone in the Sudbury area is 3750 m thick. Roughly 4150 m of section is missing between Sudbury and Wanapitei Lake. One of the reasons for this considerable thinning is the absence of some Huronian Supergroup formations. As an example, the whole of the Elliot Lake Group, and also part of the Hough Lake Group, including Ramsay Lake and Pecors formations, appear to be missing at Ashigami Lake in Scadding Township. Here, the Mississagi Formation is the oldest formation of the Huronian Supergroup and it unconformably overlies Archean basement rocks (Dressler 1979).

Paleoflow studies by Debicki (1990) provide information about the sources for each of the Huronian Supergroup formations. These data help to explain why, in the area east of Sudbury, some of the Huronian Supergroup formations are present as small patches, while in other areas they are not present at all. For example, paleoflow data from the McKim Formation indicate that flow during its deposition was generally to the west (Debicki 1990).

Data of types described above have been used in this study to reconstruct stratigraphy in the study area on both sides of the Grenville Front boundary fault and to make correlations with adjacent Southern Province geology (*see* "Stratigraphic Correlation between Southern Province and Grenville Front Tectonic Zone Rocks").

Structural Geology of the Southern Province

Faults are common within the Southern Province. Most significant is the east-trending Murray fault zone (Figure 3), which may have been active for many hundreds of millions of years (Sims et al. 1981). Card and Hutchinson (1972) found evidence that the Murray fault zone originated prior to Huronian sedimentation and was originally part of a graben system forming a depositional basin for Huronian sediments (Fueten et al. 1992). Movements along faults in the Southern Province have often been complex. For the Murray fault zone, there is evidence for down-faulting of the southern blocks during Huronian sedimentation, followed by uplift of the southern blocks in the post-Huronian time (Card et.al. 1972). During late deformation, the Murray fault zone became a southerly dipping thrust fault (Cooke 1946; Zolnai et al. 1984) with considerable right lateral displacement (e.g., Cooke 1946; Card 1968; Zolnai et al. 1984). Zolnai et al. (1984) concluded that 10 to 15 km of structural relief exists across the Murray fault zone, and attributed late brittle right-lateral movements on the Murray fault to be due to northwest-southeast compression during the Grenville orogeny at 1.0 Ga (Cumming et al. 1955; Stockwell 1964).

In the eastern Southern Province, supracrustal rocks are moderately to intensely deformed into open to sub-isoclinal folds and exhibit relatively well-developed foliations and lineations. The folds trend east to northeast, subparallel to the Murray fault zone.

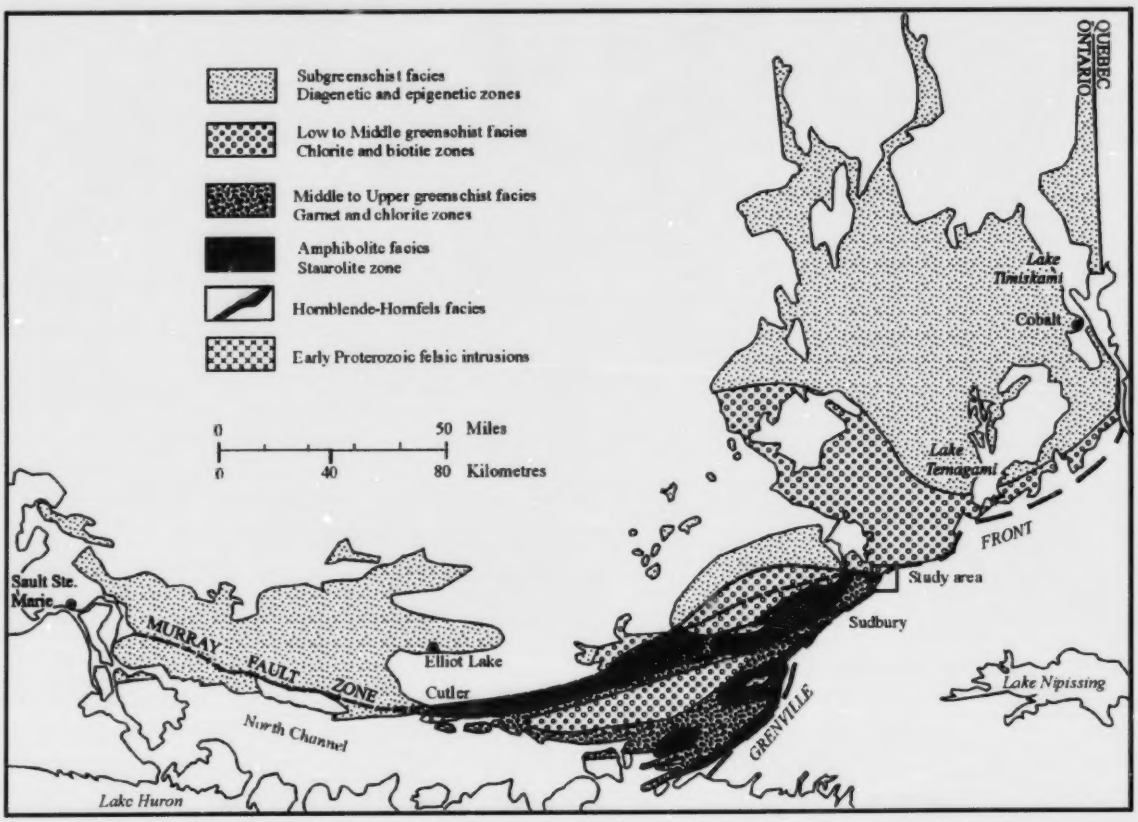


Figure 3. Patterns of metamorphism in the eastern part of the Southern Province (*modified from* Card 1978).

Proximal to the Grenville Province, Neoproterozoic cataclasis, mylonitization, and accompanying recrystallization, related to the Grenville Front tectonic zone (Lumbers 1975), are superimposed upon the major folds described above. In the Southern Province, supracrastal rocks near the Grenville Front boundary fault have been refolded about southeast-dipping axial planes, which are subparallel to the boundary fault (Dalziel et al. 1969; Lumbers 1978; Davidson 1992).

Metamorphism of the Southern Province

Paleoproterozoic rocks in the Lake Huron region show systematic differences in intensity and style of deformation, regional metamorphism and igneous activity that generally conform to their asymmetric depositional pattern. Changes are most abrupt and notable across the Murray fault zone. The Murray fault zone marks a sharp transition from relatively thin, weakly deformed and weakly metamorphosed supracrustal rocks in the northwest part of the Cutler–Elliot Lake area to relatively thick, highly deformed, moderately metamorphosed rocks southeast of it (Card et al. 1972; Sims et al. 1981) (Figure 3).

Metamorphism of supracrustal rocks in the eastern Southern Province is moderately intense and ranges from lower greenschist to lower amphibolite facies (Card 1964, 1978). It is a low-pressure intermediate type of metamorphism (Miyashiro 1961; Winkler 1967). Amphibolite facies rocks containing staurolite, andalusite, and rarely kyanite-bearing assemblages occur in northeast-trending zones. Figure 3 demonstrates the distribution of these zones; one of them lies immediately south of the Murray fault zone and the other immediately northwest of the Grenville Front tectonic zone. Within each zone, the highest grade rocks form an elliptical "nodal" distribution.

The main regional metamorphism in the Southern Province culminated after intrusion of the Nipissing gabbro suite at 2.22 Ga (Corfu and Andrews 1986; Noble and Lightfoot 1992) and prior to emplacement of the Sudbury Igneous Complex at 1.85 Ga (Krogh et al. 1984). Rb/Sr whole-rock dating of Huronian metasedimentary rocks suggests that the metamorphic culmination occurred at about 1.9 Ga (Fairbairn et al. 1969), at approximately the same time as the Penokean metamorphic culmination in the Lake Superior region (Van Schmus 1976). There is also geological, radiometric and paleomagnetic evidence for earlier pre-Nipissing gabbro suite (2.2 Ga) deformation and weak metamorphism (Card 1978).

After deposition of the Whitewater Group and emplacement of the Sudbury Igneous Complex, there was further deformation and low-grade metamorphism, followed by intrusion, at 1.75 Ga, of granite plutons within the Southern Province and adjacent Grenville Province (Davidson et al. 1992; Sullivan and Davidson 1993; Davidson and van Breemen 1994). The post-Sudbury Igneous Complex deformation and retrograde metamorphism is concentrated in areas south of the Murray fault, notably in the area between the Sudbury Structure and the Grenville Front.

GRENVILLE PROVINCE

Introduction

The Grenville Orogen of Ontario and northern New York State can be subdivided into several belts. From the northern margin of the orogen they are 1) the Grenville Front tectonic zone, 2) the Central Gneiss Belt, 3) the Central Metasedimentary Belt, and 4) Central Granulite Terrane (Wynne-Edwards 1972) (Figure 4). The Central Gneiss Belt is characterized by dominantly felsic gneisses of amphibolite to

granulite metamorphic facies. To the southeast, the Central Metasedimentary Belt separates the Central Granulite Terrane from the Central Gneiss Belt. The Central Metasedimentary Belt consists primarily of marbles, quartzites, and mafic volcanic rocks metamorphosed at the greenschist to granulite facies during the Grenville orogeny (Davidson et al. 1991; Easton 1992). The rocks that occur on the south side of the Grenville Front and within the Grenville Front tectonic zone are composed of deformed and moderately to highly metamorphosed schists and gneisses. The protoliths for most of these rocks are uncertain, although there have been various proposals correlating these gneisses with the rocks of adjacent geological provinces, specifically the Southern and Superior provinces. Quirke and Collins (1930) initially discussed this topic, that is, "disappearance of the Huronian", and it is revisited in some detail in this study.

Grenville Front Tectonic Zone

The study area is located within the northwest margin of the Grenville Front tectonic zone. Easton (1992) and Davidson (1997) have presented data and reviews of literature dealing with the nature of the tectonic zone and the position of the Grenville Front; both topics are examined in this research project.

The Grenville Front tectonic zone forms the northernmost domain of the Grenville Province (Figure 4). It is a zone as much as 30 km wide and 2000 km long (in Canada); its boundaries are gradational and are defined by visible cataclastic zones, which extend into the adjacent Southern and Superior provinces.

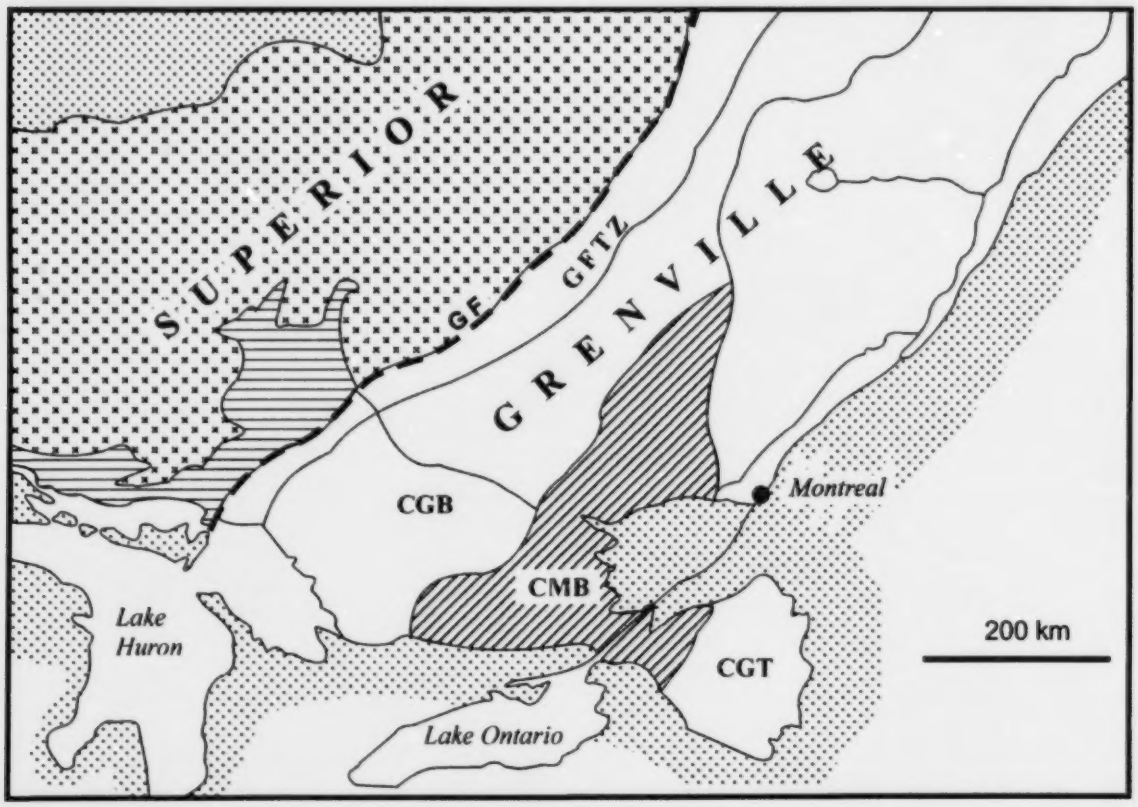


Figure 4. Subprovinces in the Grenville Province *after* Wynne-Edwards (1972) (figure *from* Davidson 1986). Abbreviations: CGB, Central Gneiss Belt; CBT, Central Granulite Terrane; CMB, Central Metasedimentary Belt; GF, Grenville Front; GFTZ, Grenville Front tectonic zone. Stippled hatching indicates Paleozoic cover; striped hatching indicates Southern Province.

Lumbers (1975, 1978) first characterized the Grenville Front tectonic zone "as a zone exhibiting a northeast-trending cataclastic foliation and southeast-plunging lineation within mainly gneissic rocks southeast of the Grenville Front Boundary Fault" (Lumbers 1975). In this definition, the Grenville Front tectonic zone includes a zone, as much as 6 km wide, in the adjacent Superior and Southern provinces, which also exhibits this fabric.

Grenvillian structures and metamorphism of the Grenville Front tectonic zone are superimposed on older protoliths that likely represent Southern and Superior province lithologies. Easton (1992) recognized three main zones within the Grenville Front tectonic zone in Ontario. In Segment 1, in the Killarney–Sudbury area, the dominant rock types are orthogneisses and minor paragneisses most likely derived from the Killarney Magmatic Belt. In Segment 2, which stretches from Sudbury to River Valley, the predominant rock types are para- and orthogneisses, as well as metagabbroic and meta-anorthositic bodies. Rocks in Segment 2, which includes the study area, were most likely derived from the Superior and Southern provinces. Finally, Segment 3, which stretches from River Valley to the Ottawa River, consists mainly of ortho- and paragneisses most likely derived from the Superior Province. Apart from the mapping of Lumbers (1973, 1975), rocks in Segment 2 of the Grenville Front tectonic zone have received little recent geological study.

U/Pb zircon age determinations have demonstrated the presence of Archean rocks within Segment 2 in the Hagar area (Chen et al. 1995) (Figure 1) and within Segment 3 south of Temagami (Krogh 1994). In addition, Nd/Sm model ages (Dickin and McNutt 1989, 1990) indicate an abundance of Archean and Paleoproterozoic rocks within Segments 2 and 3 of the Grenville Front tectonic zone. Segment 2 contains isolated remnants of Sudbury swarm diabase dikes, locally cutting an earlier gneiss fabric (Davidson 1994, 1997, 1998; Easton et al. 1996), indicating that deformation occurred both prior to, and post-1.24 Ga. Only the deformation that occurred after 1.24 Ga can be considered as truly "Grenvillian" in nature. Pegmatite dikes from Segments 1 and 3 of the Grenville Front tectonic zone in Ontario regularly yield ages of 995 to 1000 Ma (Krogh 1994), reflecting the waning stage of the Grenvillian orogeny.

The Grenville Front tectonic zone south and east of Sudbury has been mapped by Grant et al. (1962), Pearson (1962), Kwak (1968), Brown (1968), La Tour (1981), Lumbers (1975), Davidson (1992, 1998) and Davidson and Ketchum (1993). Rocks units in this area are distinctive, particularly the kyanite-bearing schists and gneisses, which contrast with the sillimanite-bearing gneisses typical of the rest of the Grenville Front tectonic zone and the Central Gneiss Belt. Primary sedimentary features in metasedimentary rocks within Grenville Front tectonic zone are rarely preserved, however, Davidson (1997, 1998) has described metaconglomerate gneisses, which occur southeast of the Grenville Front near Coniston, Ontario, that locally exhibit relatively well-preserved clasts. Similar evidence of preserved primary features such as conglomeratic clasts and sedimentary bedding within metapelites are described by Easton et al. (1996) in the Timmins Creek area (Street Township) in a zone between the Grenville Front boundary fault and the Ess Creek fault, and also south of the Grenville Front boundary fault in southeastern Street Township.

The Grenville Front tectonic zone south and east of Sudbury includes a variety of mafic and minor ultramafic gneisses. Two main types of mafic gneisses have been recognized in this region (La Tour 1979; Easton 1996; Easton and James 1997a), these may be further divided into several subtypes on the basis of field and geochemical characteristics, as follows

1. migmatitic mafic gneiss ("Grenvillian" gneiss of La Tour (1979))
   a. typically garnet-bearing, fine- to medium-grained amphibolites with lenticular leucosome (possibly derived from mafic flows and tuffs)
   b. locally, garnet-bearing, medium-grained amphibolites with podiform leucosome (possibly derived from mafic intrusions)

2. non-migmatitic mafic gneiss ("Nipissing" rocks of La Tour (1979))
   c. dark green to black, weakly layered, medium-grained, pyroxene-bearing amphibolites, anorthositic gabbro and gabbroic anorthosites. Associated with these rocks are pods of orthopyroxene hornblendite (all the above rock types may be part of a layered igneous intrusion). Texturally, some of these rocks resemble the pseudo-diabasic textured rocks described below, and it is uncertain if these rocks are related to the Nipissing gabbro suite or to the East Bull Lake intrusive suite.
   d. green, pseudo-diabasic textured, medium-grained amphibolites. Texturally, these rocks resemble rocks of the Nipissing gabbro suite, and are chemically similar to that suite.

The presence of a well-developed leucosome phase in the some of the mafic gneisses suggests that there was an early high-grade metamorphic (and deformational) event in the area prior to Nipissing magmatism, and that the non-migmatitic gneisses were emplaced into the area subsequent to this early event, but prior to the main, preserved, regional metamorphic event.

All of the rocks within the Grenville Front tectonic zone south and east of Sudbury have been subjected to high-grade regional metamorphism between about 1.3 and 1.0 billion years ago (Lumbers 1971, 1975) and, as a result, were converted into coarsely recrystallized schists and gneisses. Thermobarometric data show that most of these rocks experienced medium pressure (7 to 9 kbar) and temperature (500 to 700°C) metamorphism (e.g., Kwak 1971; La Tour 1981).

On the Grenville side of the Grenville Front tectonic zone, rocks are typically deformed into tight isoclinal folds whose axial planes strike northeast and plunge moderately to steeply southeast. All of the units forming such folds are penetratively deformed at centimetre to metre scale. Typically, most rock units have experienced two periods of deformation. Within the adjacent Southern and Superior provinces, rocks exhibit mostly brittle deformation in the form of a cataclastic foliation which is parallel to the northeast trend of the Grenville Front.

As part of the Abititbi–Grenville Lithoprobe project, the Grenville Front tectonic zone has been imaged as a southeast-dipping region of anomalous velocity gradients (high velocity crust south of the Grenville Front and relatively lower velocity crust to the north) which extends to the Moho (Green et al. 1988; Winardhi et al. 1997). The Grenville Front tectonic zone has pronounced seismic expressions that indicate a thickening of the crust by 5 to 8 km. Compared with the rest of the Grenville Province, the Grenville Front tectonic zone in Ontario has unique geophysical characteristics (seismic, magnetic, and gravity) compared with the Grenville Front tectonic zone in Quebec and Labrador.

The Grenville Front

The Grenville Front can be defined in several ways, viz: as a metamorphic boundary, a structural boundary, a geochronologic boundary (particularly using Rb/Sr, K/Ar and Ar/Ar isotopic systems) and a lithological boundary. In the area south and east of Sudbury, the boundary has been defined as either a metamorphic transition or a discrete fault.

Lumbers (1978) stated that the Grenville Front marks a thermal boundary resulting from the influx of mantle heat into rocks of the Grenville Province during Mesoproterozoic high-grade regional metamorphism. In the area directly southeast of Sudbury, Phemister (1961) and Grant et al. (1962) interpreted the boundary between the Southern and Grenville provinces as a metamorphic transition. They proposed that Huronian sedimentary rocks and Nipissing gabbro in this area had been metamorphosed and granitized to form the gneissic and migmatitic rocks of the Grenville Front tectonic zone. Kwak (1971) and La Tour (1981) have documented a transition from lower to middle greenschist facies rocks to

upper amphibolite facies gneisses and migmatites over a few hundred metres southward from the Grenville Front, east of Sudbury.

Several researchers have carried out structural studies in the area between the Grenville Front and Wanapitei fault in the Sudbury area. Phemister (1961) concluded that the Wanapitei fault cut the Grenville Front in this area. In contrast, Dalziel et al. (1969) suggested that the Grenville Front and the Wanapitei fault are coincident. He also recognized that the Grenville Front is typically marked by a zone of intense mylonitization and, in certain areas, (i.e., the Crerar area) a brecciated mylonite zone indicates that repeated periods of mylonitization occurred along the Front. More recent studies by Davidson (1992, 1997) show that the Wanapitei fault becomes coincident with the Grenville Front east of Coniston near the southwest corner of Street Township (Figure 5). Easton et al. (1996) suggested that in northeastern Street Township, the Grenville Front–Wanapitei fault is coincident with the Ess Creek fault. This study addresses, in part, the validity of this latter suggestion.

GEOLOGY OF STREET TOWNSHIP

Introduction

As the thesis area represents a small area of Street Township (Figure 6), a brief geological review of the geology of Street Township is in order for the following reasons: 1) the author was involved in mapping part of the Grenville Province within Street Township; 2) many of the geological units within the thesis area occur throughout Street Township, and locally, are better exposed and studied outside of the thesis area; and 3) the township has only been recently mapped, and much of the geology of this area remains unpublished as of this writing.

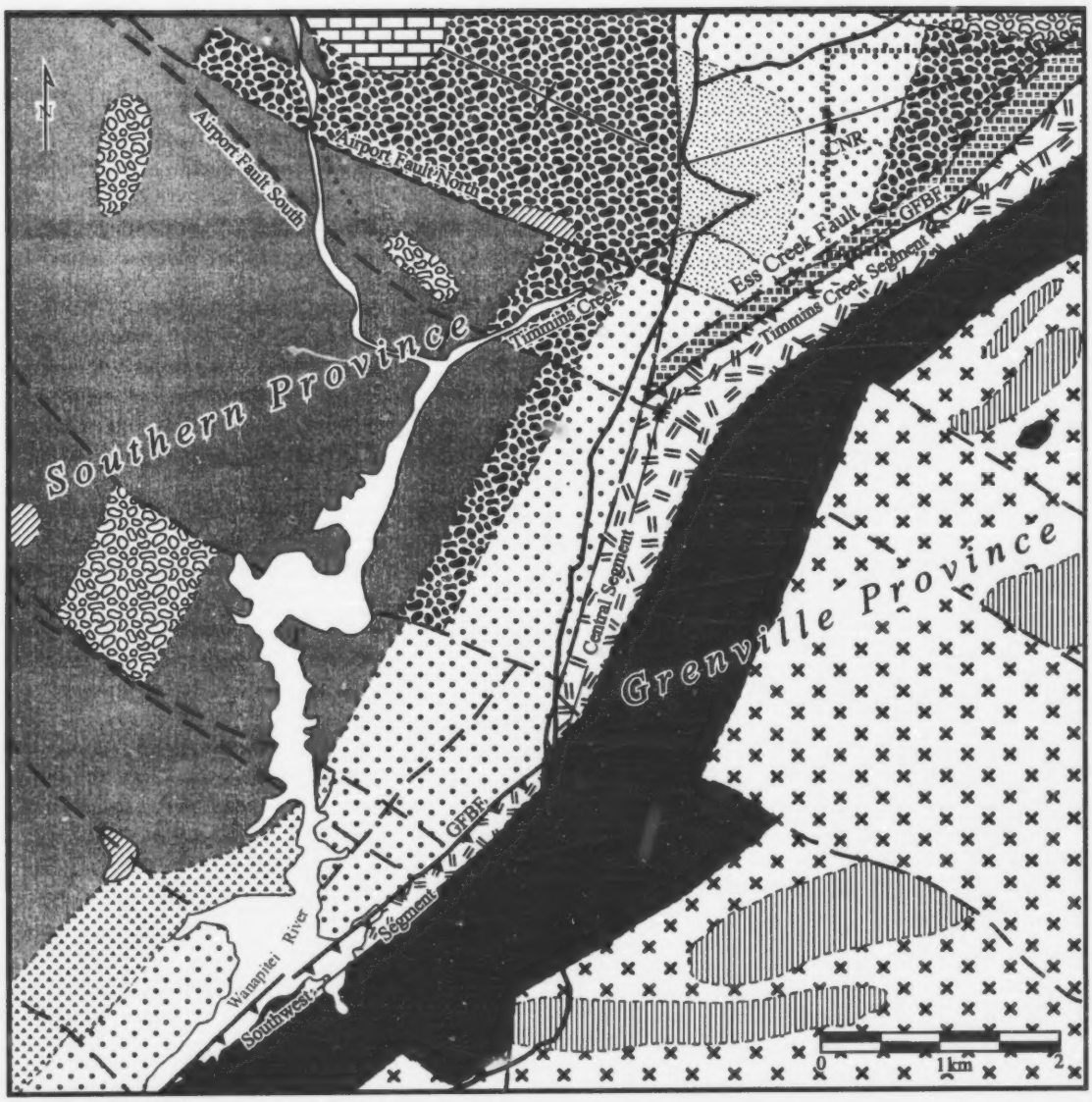
Rocks within Street Township occur within three distinct zones, a zone of Southern Province strata, a zone of Grenville Province strata, and a zone of transitional rocks located between the two provinces in the northeastern part of the township. Part of the goal of this thesis is to elucidate whether rocks of the Transitional Zone should be assigned to either the Southern or Grenville province, and, if so, what criteria should be used for this assignment. The geology of each of these zones is described in turn below.

Southern Province

The rocks of the Huronian Supergroup occur in three domains and their distribution is shown in Figure 5. East of the Wanapitei River, an exposed section through the Hough Lake and Quirke Lake groups is recognized; top-directions in this section face west. The Bruce Formation in this section is less than 350 m thick, and the Espanola Formation is less than 80 m thick. The maximum metamorphic grade in this domain occurs 200 m west of the Grenville Front near Jackson Lake where it reaches biotite grade in pelitic rock compositions (Easton et al. 1996).

West of the Wanapitei River, Serpent Formation quartzite is the dominant lithology. There are also local occurrences of discomformably overlying Gowganda Formation conglomerate. These units form a homoclinal sequence, which is northwest facing. Sills of Nipissing gabbro locally intrude along the Serpent–Gowganda contact.

Hough Lake and Quirke Lake groups strata are also exposed in northern Street Township. Here, the Bruce and Espanola formations are thicker (over 500 m and 200 m, respectively). North of the Ess Creek



Grenville Province

- Domain 1: garnet-biotite (+ or - kyanite) gneisses and amphibolites with a strong foliation which is parallel to the Front
- Domain 2: migmatitic and non-migmatitic amphibolites (+ or -), quartzo-feldspathic garnet gneisses (+ or - kyanite, muscovite), and Sudbury diabase
- Domain 3: migmatitic quartzofeldspathic gneisses which wrap around dominantly non-migmatitic rocks of domain 4
- Domain 4: consists cpx - bearing coarse grained amphibolites and anorthositic gabbro, and migmatitic granitic gneisses

Southern Province

- Nipissing Diabase
- Cobalt Group: Gowganda Formation
- Quirke Lake Group: Serpent Formation
- Quirke Lake Group: Espanola Formation
- Quirke Lake Group: Bruce Formation
- Hough Lake Group: Mississagi Formation
- Hough Lake Group: Pecors Formation

- Transitional Zone
- zone of silicification and Na-metasomatism
- geological contact
- fault
- Study area

Figure 5. Simplified geological map of Street Township (*modified from* Easton 1996).

fault and the Airport fault, these formations form broad anticlines and synclines; their axis strike at approximately 070°, quite different from the strike of the homoclinal sequence to the southwest (Figure 5). No metamorphic biotite has been identified to the north of the Ess Creek fault, indicating that metamorphism has not exceeded the chlorite zone in metapelitic rocks.

The Airport fault, which trends east-southeast, marks a change in stratigraphy of the Huronian strata. North of this fault, the Bruce and Pecors formations become more dominant (Figure 5).

Transitional Zone Strata

Metavolcanic and metasedimentary rocks that occur between the Ess Creek fault (south branch) and Grenville Front boundary fault (Lumbers 1973) were tentatively correlated with formations within the Elliot Lake Group of the Huronian Supergroup by Easton et al. (1996). These rocks have been deformed and metamorphosed to low to middle amphibolite facies. They consist of white-mica schist, foliated felsic and mafic metavolcanic rocks (originally noted by Lumbers (1973), polymictic conglomeritic schist, garnet-biotite schist ± muscovite ± staurolite, minor garnet-bearing amphibolite and foliated granite. A large body of semiconformable foliated amphibolite occurs in this terrain and may represent metamorphosed Nipissing gabbro.

This package of rocks forms the so-called Transitional Zone and occurs between the greenschist facies rocks of the Southern Province and highly deformed and metamorphosed gneisses of the Grenville Province (Figure 6). Rocks in this zone are the main focus of the present thesis study, and as such, are described in detail in the next chapter.

Grenville Province

In Street Township, the Grenville Province can be described in terms of four lithotectonic domains (Figure 5), all of which are oriented roughly parallel to the Grenville Front (Easton 1996). Domain 1 occurs along the Central and Timmins Creek portion of the Grenville Front (Easton 1996). This domain is composed of biotite-garnet, biotite-garnet-kyanite, garnet-amphibolite gneisses and Nipissing metagabbro. There is a strong penetrative foliation throughout these rocks, which parallels the Grenville Front boundary fault. There are also migmatitic, garnet-absent granite gneisses in this domain that may be Archean or Proterozoic in age. At least two stages of deformation are recognizable in these rocks. Clear evidence of the folding of a S_1 foliation indicates the existence of a second stage (F_2) of deformation. Occurrence of two generations of pegmatites and quartz-feldspar migmatites are common features in this domain. More detailed information about rock types, structure and metamorphism of this domain is presented in a subsequent parts of this report.

Domain 2 includes garnet rich gneisses and is typified by thin lithologic units, which exhibit an interference fold pattern dominated by a variably plunging, northeast trending synform. An apparent stratigraphy is present (Easton 1996), as follows:

1. highly deformed, migmatitic, garnet (5 to 10%) amphibolite;
2. gneiss including muscovite- and kyanite-bearing varieties, along with layers of garnet-rich mafic and garnet-gedrite gneisses. Rare feldsparthic, quartzose, metapelitic and metaconglomeratic paragneisses are also present.
3. migmatitic garnet (5 to 10%) amphibolite with plagioclase rims and wings developed around the garnets; and

4. non-migmatitic, typically garnet-absent, clinopyroxene-bearing, weakly ophitic, amphibolite, locally showing cross cutting relationships with units 1 to 3. This is the only domain which contains preserved, folded and boudinaged, segments of the circa 1.24 Ga Sudbury diabase dike swarm.

Domain 3 consists of migmatitic (>20% leucosome), garnet-bearing to garnet-rich quartzofeldspathic gneisses. These gneisses surround large masses and enclaves of mainly non-migmatitic orthogneisses and rocks of Domain 4. The migmatitic gneisses are highly folded on an outcrop scale.

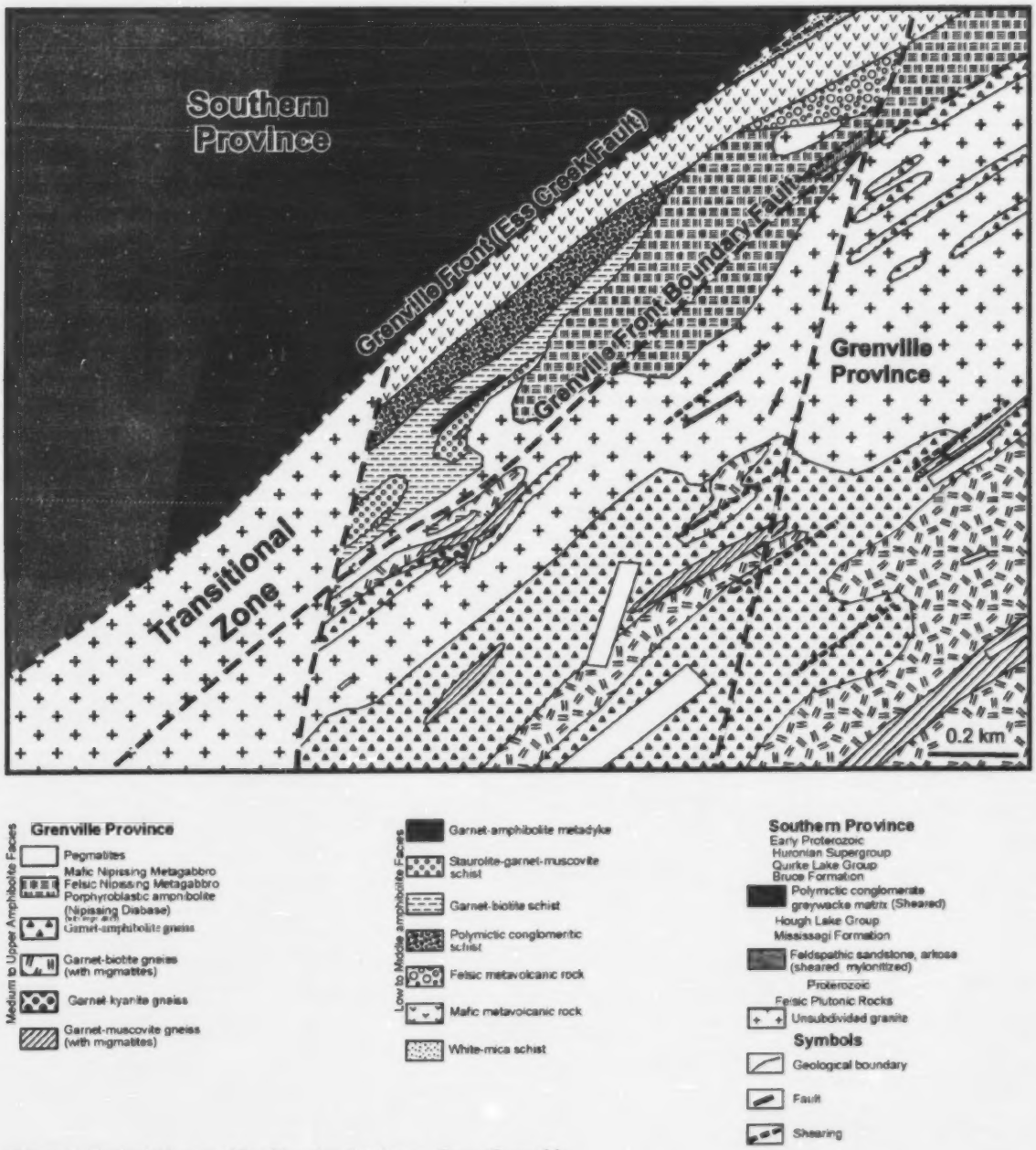


Figure 6. Geological map of the Timmins Creek area, Street Township.

As noted above, Domain 4 consists of large enclaves of orthogneiss. Two main types of orthogneiss are present. The first type is a clinopyroxene-bearing, gabbroic textured, foliated to gneissic amphibolite, and associated anorthositic gabbro to gabbroic anorthosite. This orthogneiss was recently mapped in detail by Easton (1999). The second orthogneiss is a migmatitic, granodiorite-monzogranite gneiss, which yields U/Pb emplacement ages of circa 2460 Ma (Corfu and Easton 1998, in press).

Geology and Structure of the Timmins Creek Area

DESCRIPTION OF STRATIGRAPHIC UNITS

Southern Province: Huronian Supergroup

INTRODUCTION

Rocks of the Mississagi Formation and the Bruce Formation occur in the northwest part of the thesis area (Figure 6). The Mississagi Formation consists of metasandstone, thin layers of meta-argillite and locally metaconglomerate; the Bruce Formation consists of metamorphosed polymictic conglomerate. Both of these formations were deformed, folded and locally exhibit decametre long, discontinuous, strongly foliated zones striking parallel to the Ess Creek fault. The 2219 to 2210 million-year-old Nipissing gabbro (Corfu and Andrews 1986; Noble and Lightfoot 1992) occurs as sills within these formations and crops out in the northeast part of the Street Township, just north of the upper boundary of the thesis study area. Figure 6 is a simplified version of the more detailed geologic map of the area included in the back pocket. Rock unit descriptions that follow are keyed to the legend of the map (back pocket) and Figure 6.

MISSISSAGI FORMATION

Rocks of the Mississagi Formation form a northeast-trending band across northwestern corner of the study area. The Mississagi Formation in the area consists of tan to grey, medium- to coarse-grained quartzite that weathers tan to buff, grey and rusty in colour, with minor amounts of fine- to medium-grained metawacke and metasiltstone. Coarse-grained varieties of quartzite contain pebbles elongate parallel to the foliation that strikes at 027 to 030°; pebble size is 0.5 to 1 cm along the short axis and 1 to 2 cm in length.

Evidence of folding in Huronian strata is present in Mississagi Formation on the northern side of the Canadian National Railway line (Photo 1). Drag folds occur on the southwest side of an anticline with the axial plane striking at 100 to 140° and fold hinge plunging 34°SW. Metamorphic foliation oriented at 050 to 055°/70°SE is parallel to bedding. Cross- and graded bedding is common in these rocks and indicates that the top of sedimentary layers faces northwest.

In the study area, rocks of the Mississagi Formation is disrupted by numerous faults, documented in the core logging of Gulf Minerals Limited (Craigie 1976) and also by narrow, local shear zones striking at 060°. The shear zones that cut the Mississagi Formation show variation in width from centimetres to one metre and variable degrees of intensity of deformation. In general, the fabric of the matrix is slaty, highly tectonized and contains rotated blocks of quartzite (Photo 2). The sheared rocks have a strongly foliated

Photo 1. Drag fold in quartzite of the Mississagi Formation. Outcrop is located in the Southern Province, 350 m north of the Ess Creek fault along the abandoned Canadian National Railway line. Hammer handle is 35 cm long.

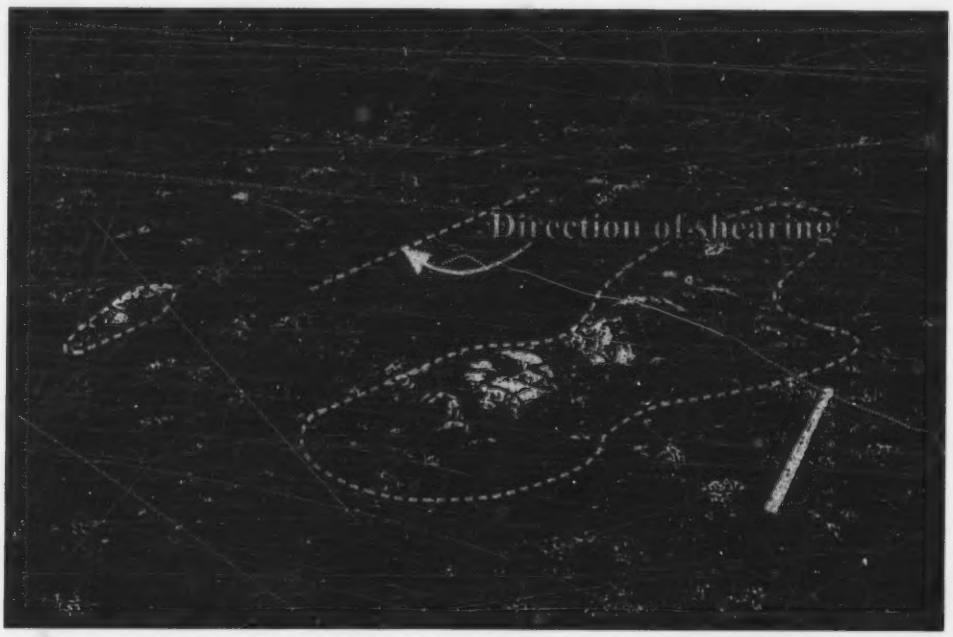


Photo 2. Shear zone within quartzite of the Mississagi Formation. Pods of underformed quartzite are outlined. Southern Province, outcrop 3002. Hammer handle is 35 cm long.

schistose matrix that encloses rotated blocks of quartzite in the largest shears and centimetre-wide lozenge-shaped quartzite in smaller scale shears. It is conceivable that the large-scale zones possibly represent Sudbury Breccias or similar to the breccias which occur on the north side of the Murray Fault.

BRUCE FORMATION

Rocks of the Bruce Formation are folded into broad, plunging, northeast trending synclines and anticlines in the northern part of the Street Township. In the study area, the Bruce Formation forms the southeast side of an anticline and is greater than 500 m thick (apparent thickness). The Bruce Formation overlies the Mississagi Formation, but the contact between them in the thesis area is not exposed; elsewhere Debicki (1990) has described it as gradational.

The Bruce Formation consists of metamorphosed polymictic conglomerate, that is dark grey and rusty grey to brown on the weathered surface. There are at least two varieties of pebbles, quartzite and argillite, with maximum dimensions from 1 to 7 cm. Argillite pebbles are more flattened and elongate compared with those of quartzite composition, but both have a subrounded to subangular shape. The attitude of metamorphic foliation in the metaconglomerate is 060°/80°SW. Discontinuous and narrow shear zones, similar to those described for Mississagi quartzite, occur in the Bruce metaconglomerate, but are less abundant.

Transitional Zone

LOW TO MIDDLE AMPHIBOLITE FACIES

Introduction

In the central and southeast part of the study area, metavolcanic and metasedimentary rocks south of the Ess Creek fault, and north of the Grenville Front boundary fault have been tentatively correlated with formations in the Elliot Lake and Hough Lake groups of the Huronian Supergroup (Easton et al. 1996). These rocks are the focus of this study. They form a Transitional Zone from greenschist facies rocks on the northwest side of the Ess Creek fault (Mississagi and Bruce formations) to the highly deformed and metamorphosed upper amphibolite facies rocks on the southeast side of the Grenville Front boundary fault. The mineral assemblages in these metapelitic and metabasitic rocks were formed as a result of metamorphism at conditions of low- to medium-grade amphibolite facies; as described in detail in a subsequent section.

Bodies of mafic and felsic metavolcanic rocks that occur in the Transitional Zone south of the Ess Creek fault are correlated with the Stobie Formation (Elliot Lake Group) on the basis of lithological similarities, stratigraphic position and whole rock geochemistry (*see* "Geochemistry"). In the Transitional Zone south of the metavolcanic units, polymictic conglomerate is common, and garnet-biotite, and staurolite-garnet-muscovite schists exhibit well-preserved sedimentary features. It is possible to identify the compositions of pebbles in the conglomerate unit and to distinguish graded bedding in sand-rich layers within the mica-bearing schists. Based on lithological characteristics, stratigraphic position and whole rock geochemistry, these rocks are tentatively correlated with the Pecors and Mississagi formations (Hough Lake Group) although the presence of some Stobie Formation metasedimentary rocks cannot be entirely precluded.

Strata of these schistose rocks are folded into isoclinal, variably plunging, northeast-trending folds. Rock units proximal to the Ess Creek fault are highly foliated and exhibit tight isoclinal folding (Photo 3). There are well-preserved drag folds of quartz and feldspar-rich layers on a microscopic scale within the different schist units. The northeast-oriented foliation (S_1) of the area is, in general, parallel to the primary bedding (S_0), where it is observed in the limbs of folds. However, in the nose of folds the foliation typically cuts the bedding plane at a high angle.

Large sill-like zones of Nipissing metagabbro and a mafic amphibolite dike of undefined age intrude all of these rocks (Figure 6).

White-mica schist unit (protomylonite)

This unit is approximately 100 m wide (apparent thickness) and is exposed proximal to the Ess Creek fault; it is bounded to the north by the Bruce conglomerate (Southern Province) and to the south by mafic metavolcanic rocks (Transitional Zone) (Figure 6). These rocks are fine to medium grained and consist of quartz, feldspar and white mica. Both fresh and weathered surfaces are light greenish-grey in colour. These rocks exhibit a discontinuous banding on a centimetre scale, which consists of 1) white mica rich zones that form bands 0.5 to 1 cm thick and have boudinaged, flattened quartz lenses and ribbons (some of which could be interpreted as quartz veins on a big scale), and 2) more quartz-feldspar rich layers, which are more massive, foliated, with less white-mica. This compositional layering suggests that the unit was originally layered and subsequently tectonically deformed due to shearing along the Ess Creek fault. The rocks of this unit exhibit strong foliation that may represent stages in formation of protomylonite (Photo 4). Based on the mineral assemblage, these rocks exhibit the same greenschist-facies grade metamorphism as the rocks of Bruce and Mississagi formations in the adjacent Southern Province.

Mafic metavolcanic unit

This unit consists of a 60 m wide (apparent thickness), homogeneous, foliated, fine- to medium-grained, well-banded metabasalt; the foliation has the orientation 050° to 060°/75°SE. The metavolcanic rocks continue east of the map area (Figure 6) and are cut off to the west by a northeast-trending fault documented in drill core (Craigie 1976). It is clear on weathered surfaces that the banding is due to distinct mafic (amphibole ± chlorite ± epidote) and more leucocratic (quartz, plagioclase, epidote) variations in composition. The banded rocks have been folded as indicated by small-scale S- and Z-shape isoclinal drag folds (Photo 5). These rocks appear to be flattened (tight isoclinal folds) and some could be classified as blastomylonites. Amphibole, plagioclase, with minor quartz and chlorite and lesser epidote, biotite, muscovite, titanite, iron-titanium oxides and sulphide minerals form this assemblage. Quartz veins, in some places with minor carbonate and garnet, range in size from 1 to 7 mm wide and comprise 2% of this unit. These veins are oriented parallel to the plane of foliation and are also involved in the S-type folding where they have been boudinaged (Photo 6). These rocks are preserved at amphibolite facies.

Felsic metavolcanic unit and related metasedimentary rocks

In the northeast part of the map area and stratigraphically above the mafic metavolcanic rocks, there is a small lens-shaped body of metamorphosed felsic pyroclastic rocks about 30 m wide (apparent thickness). It is underlain conformably by semipelitic metasedimentary rocks of undefined total thickness. The metasedimentary rocks are 0.6 to 1 m wide massive quartz rich sandstone layers, and 10 to 20 cm thick, mica-rich, schistose mudstone layers (Photo 7). The quartz rich metasandstones are resistant to weathering and, in some places, graded bedding is preserved, which indicates the beds face south. The matrix of the felsic pyroclastic metavolcanic rocks is foliated, greenish-grey (fresh surface) or grey to tan

Photo 3. Extreme flattening and tight isoclinal folding within mafic metavolcanic rocks found in close proximity of the Ess Creek fault. Transitional Zone, outcrop 3004. Pen is 14 cm long.

Photo 4. Strongly foliated to protomylonitic, white-mica schist, 20 m south of the Ess Creek fault within the Transitional Zone. Pen is 14 cm long.

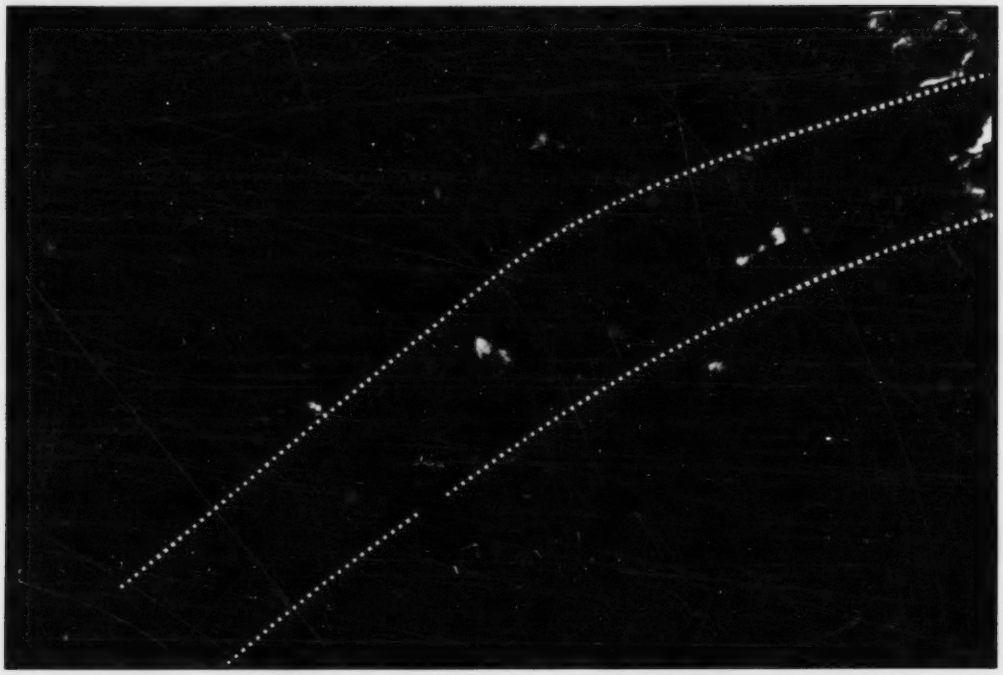


Photo 5. Bedding in mafic metavolcanic rocks, 50 m south of the Ess Creek fault, within the Transitional Zone (outcrop 3004). Bedding is obscured by S- and Z-shape microfolds, folding is accentuated be the presence of leucocratic veins. Late-stage faulting (marked by dashed line) is also present. Pencil is 14 cm long.

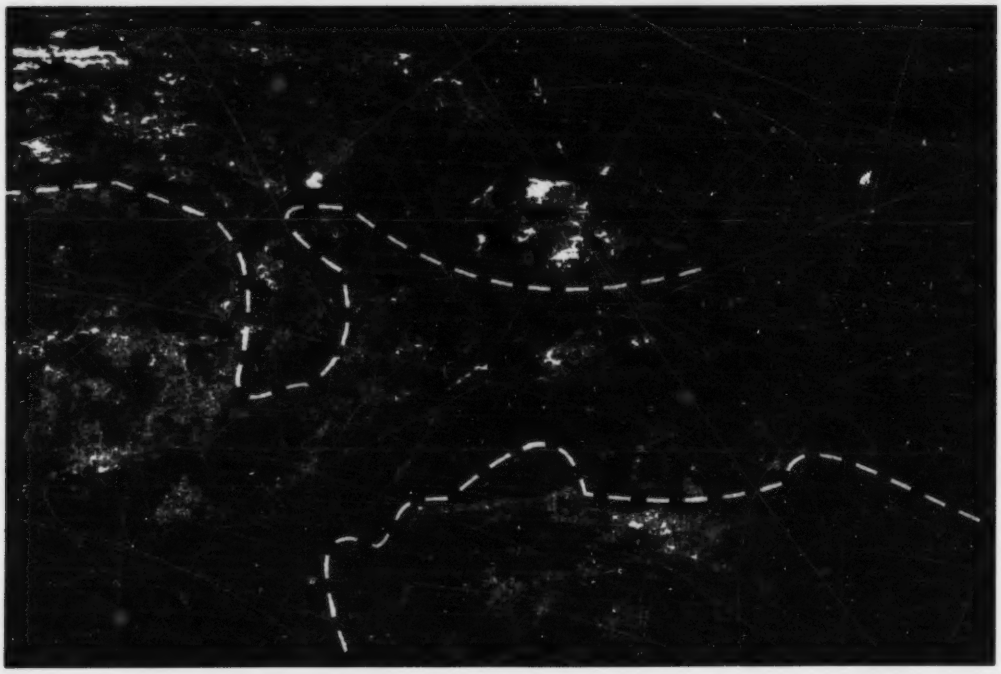


Photo 6. Quartz veins within mafic metavolcanic rocks (Transitional Zone, outcrop 3004) are common; they occur parallel the S_1 foliation, but are also folded and boudinaged. White dashed lines highlight the quartz veins. Pencil is 14 cm long.

Photo 7. Interbedded quartz- and mica-rich layers within metasedimentary rocks of the Transitional Zone, 40 m north of outcrop 3047. Hammer handle is 35 cm long.

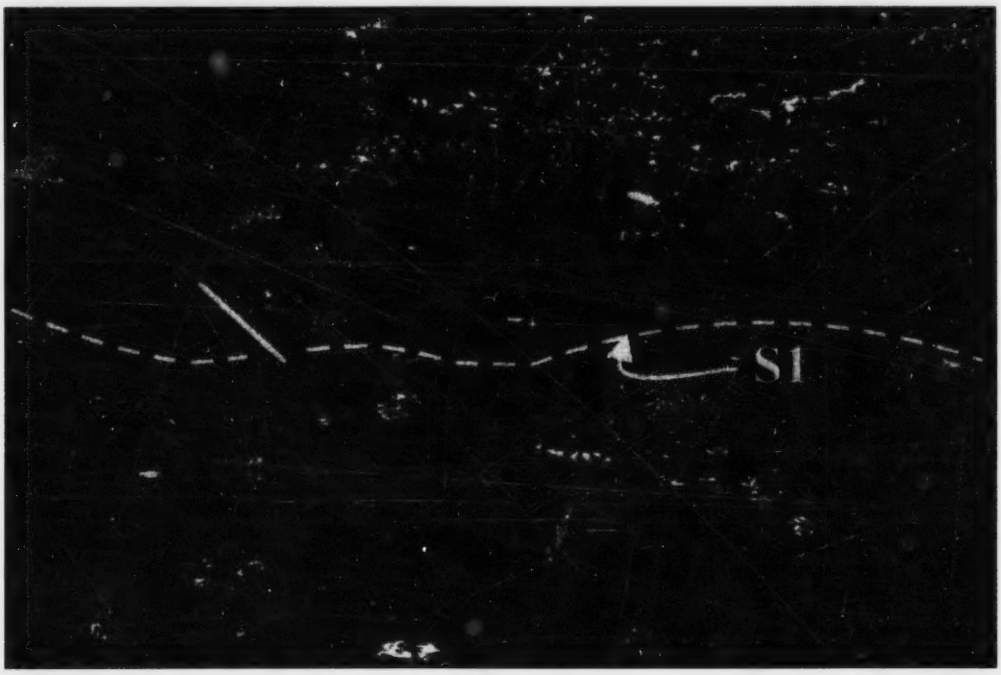


Photo 8. Stretched fragments in the felsic pyroclastic unit; fragments are parallel to S_1 foliation. Transitional Zone, outcrop 3047. Pen is 14 cm long.

coloured (weathered surface), fine- to medium-grained and composed of quartz, feldspar and amphibole, with lesser biotite. Lens-shaped "fragments" composed mostly of quartz and feldspar with 1 to 2% mafic minerals (Photo 8) are common in this unit, and are elongated in the plane of the foliation (060°E strike). The clasts are interpreted to represent thoroughly welded, recrystallized pumice shards or volcanic bombs. Although some of the "fragments" may be boudinaged layers or veins, the abundance of these fragments and their distribution suggests that many of them do indeed represent fragments (Photo 9).

Polymictic conglomeratic schist unit

In the central portion of the study area (Figure 6), the mafic metavolcanic unit is overlain by polymictic conglomeratic schist. The contact between metasedimentary and mafic metavolcanic rocks is not exposed. This schistose metaconglomerate unit is approximately 75 m wide (apparent width) and consists of metaconglomerate with a minor amount of interlayered schistose quartzite. The contact between quartzite and metaconglomerate (S_0) strikes at 050° (Photo 10). The quartzite has a whitish-grey colour and is medium grained. There are abundant boudinaged quartz veins within both quartzite and conglomerate sections of this unit. These veins are folded, with a similar fold pattern to the veins observed in the mafic metavolcanic rocks.

Grain size in this unit is varied; the average size of pebbles in the conglomerate is 0.5 to 1 cm in width and 3 to 5 cm long. These highly flattened pebbles are parallel to the strike of the foliation (060°). The pebbles vary in composition from quartzite, granite and possible metasedimentary or metavolcanic rocks (Photo 11). The matrix varies in composition, from a quartz-feldspar-mica-rich composition to more mafic, amphibole-rich versions. The grain size of the matrix is varied, ranging from medium to coarse grained. Syn- to posttectonic almandine-rich garnet is present throughout the matrix. Garnet grain size varies from 0.5 to 0.8 cm. The garnets are not clasts and are not flattened, but do exhibit pressure shadows. The main deformation that produced the foliation (S_1) in these rocks is orientated at 060°/60°SE. There is also a weakly developed foliation at 175° within this fabric, which probably developed due to folding of S_1.

Garnet-biotite schist unit

This schist lies to the south of the metaconglomerate (Figure 6) and is in sharp contact with it (Photo 12). The garnet-biotite schist is 50 to 60 m wide (apparent width), medium grained, brownish-grey in weathered surface and bimodal in composition. Fine- to medium-grained, sandy layers from 2 to 70 cm thick, predominate (approximately 80%). The remaining 20% is composed of 1 to 3 cm wide, medium-grained, mica-rich beds. As a result the unit has a banded appearance in outcrop.

This schist is composed of quartz, feldspar, biotite, minor muscovite and syn- to posttectonic, porphyroblastic garnet. Graded bedding was observed within the sandy portion of this garnet-biotite schist, but it was difficult to identify facing direction (Photo 13). In the nose of folds, bedding is at a high angle to the S_1 foliation (Photo 14); elsewhere, along the limb of folds, it is typically subparallel to parallel to foliation. In outcrops of this schist, one stage of folding (F_1) can be documented. Quartz-rich layers (possibly veins) display a similar fold pattern to the veins observed in both the mafic metavolcanic and conglomerate units.

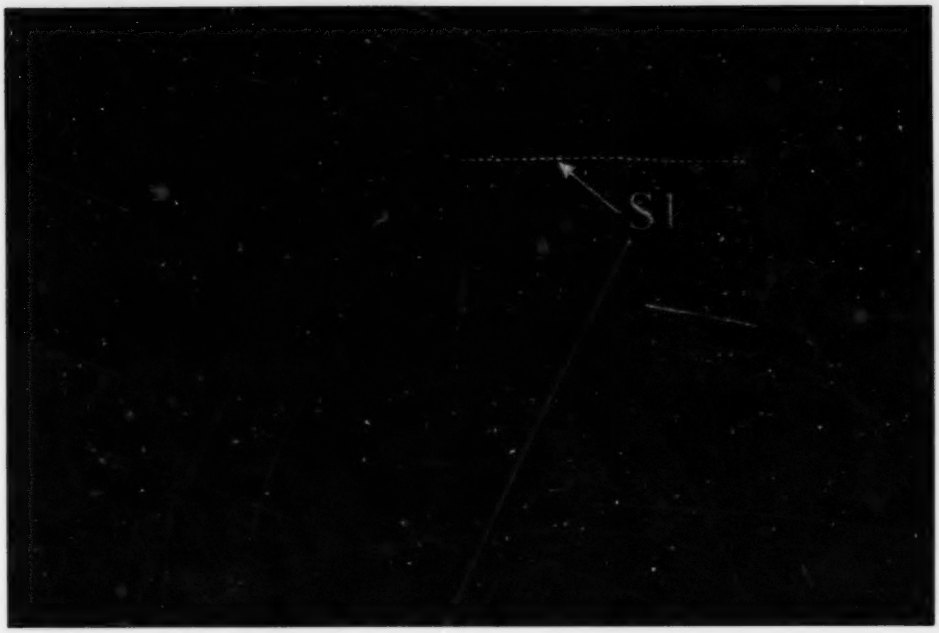


Photo 9. Stretched fragments in the felsic pyroclastic unit. The abundance of fragments suggests a pyroclastic origin, but the continuity of some fragments may indicate that they were originally layers or veins. Transitional Zone, outcrop 3047. Pen is 14 cm long.

Photo 10. Sharp contact (dashed line) between polymictic conglomerate (top) and quartzite (bottom), 70 m north of outcrop 3005 in the Transitional Zone. Pen is 14 cm long.

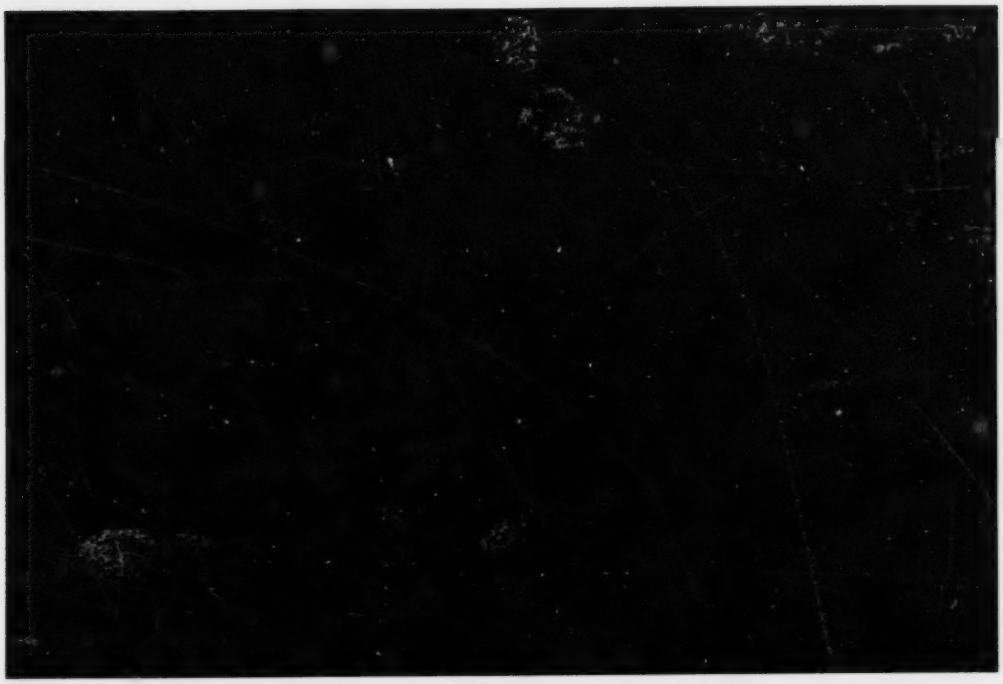


Photo 11. Polymictic conglomerate; pebbles are elongated parallel to S_1 foliation. Transitional Zone, outcrop 3005. Pen is 14 cm long.

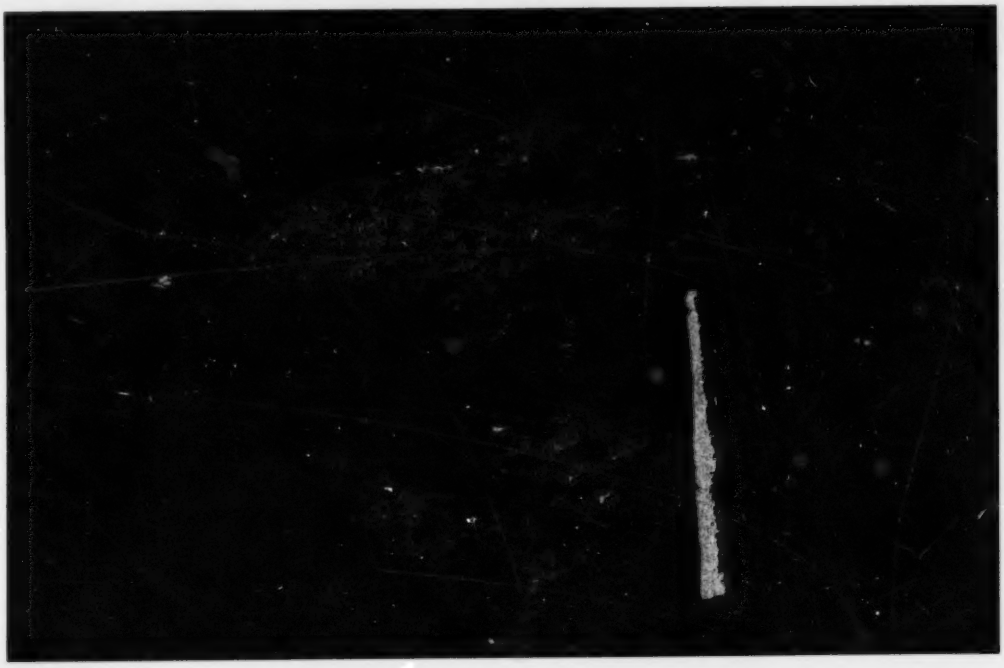


Photo 12. Sharp contact between garnet-biotite schist and polymictic conglomerate. Transitional Zone, outcrop 3031. Hammer handle is 35 cm long.

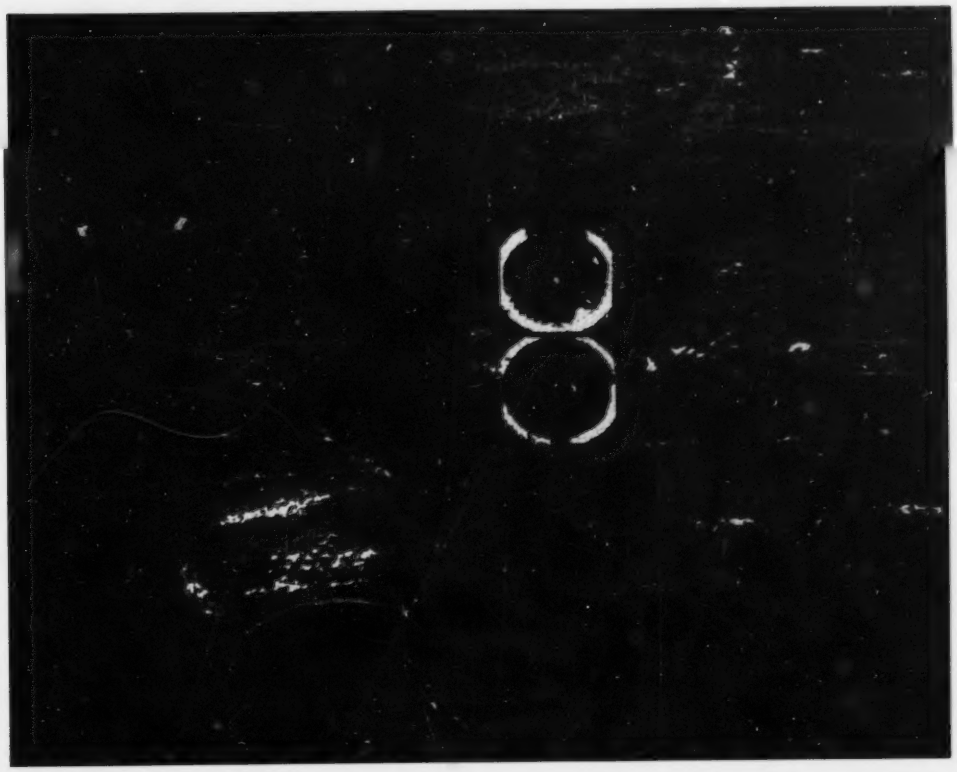


Photo 13. Graded bedding within garnet-biotite schist unit; bedding is parallel to the S_1 foliation. Transitional Zone, outcrop 3031. Compass is 8 cm in diameter.

Photo 14. Foliation (S_1) crosscuts bedding (S_0) within a fold nose (F_1). Transitional Zone, outcrop 3031. Hammer handle is 35 cm long.

Staurolite-kyanite-garnet-muscovite schist unit

This unit lies south of the garnet-biotite schist and is interpreted to overlie it. The contact between them is not exposed. Features such as bedding and similarities in metamorphic grade and fold pattern indicate that both these units formed and were deformed in a similar environment. This unit is a mixture of 10 to 70 cm thick beds of sandy semipelite and 1 to 3 cm thick beds of metamorphosed shale or mudstone (Photo 15). The colour of the weathered surface is light brownish-grey and the fresh surface is light greenish-grey. Coarse-grained muscovite-rich beds correlate with mudstone beds and medium-grained quartz-feldspar-rich layers represent sandstone. Besides quartz, feldspar and white mica, 3 to 5% garnet, staurolite, kyanite and minor biotite are present in the shaly and sandstone representatives of this unit.

The fold pattern of this unit is similar to that shown by the unit of garnet-biotite schist. Tight east-northeast-trending folds can be observed on an outcrop scale (Photo 16). In several places, an angular relationship between primary bedding (S_0) and axial planar foliation (S_1) is clearly observed (Photo 16).

Garnet-amphibolite metadike

Rocks of this unit are exposed in the central part of the map-area (Figure 6), where they cut the garnet-biotite and staurolite-garnet-muscovite schists along a northeast-trending contact (Photo 17). This rock unit consists of medium-grained, garnet-bearing amphibolite schist. Both weathered and fresh surfaces are dark grey-black in colour. These rocks are homogeneous; the parallel alignment of amphibole needles defines the northeastern trending lineation. Garnet comprises about 3 to 5% of the rock and forms 0.5 to 1 cm size porphyroblasts that exhibit cross-like shapes (Photo 18). There are no pressure shadows around garnet grains, which indicates that the garnets are posttectonic with respect to the (F_1) foliation. These rocks are sufficiently different in chemistry and mineralogy to be distinct from Nipissing metagabbro (*see* "Geochemistry").

Grenville Province

MIDDLE TO UPPER AMPHIBOLITE FACIES

Introduction

South of the Grenville Front boundary fault (Lumbers 1973), which is marked by a narrow zone of hematitic and chloritic fault gouge, there is approximately 400 m wide bend of outcrops consisting of kyanite-garnet-mica-bearing gneiss, granite gneiss, garnet-amphibolite gneisses and Nipissing metagabbro. All of these units were subjected to middle to upper amphibolite facies of metamorphism.

Garnet-biotite-amphibole gneiss unit

Rocks of this metasedimentary unit lie immediately south of the Grenville Front boundary fault (Lumbers 1973). They are well foliated, gneissic, and, in a few places, schistose, brownish-grey to dark-grey in colour, and fine to medium and, in places, coarse grained. Compositional layering that may be bedding is common (Photo 19). Mineralogy of the gneiss is quartz, plagioclase, biotite, hornblende and garnet.

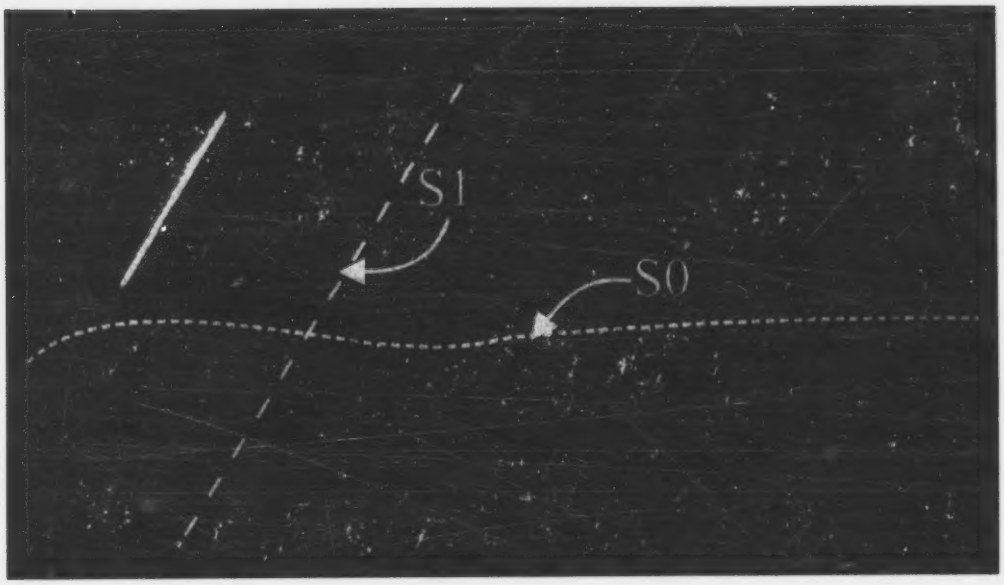


Photo 15. Compositional layering within the staurolite-kyanite-garnet-muscovite schist unit. Note that foliation (S_1) crosscuts bedding (S_0). Transitional Zone, outcrop 3112. Pen is 14 cm long.

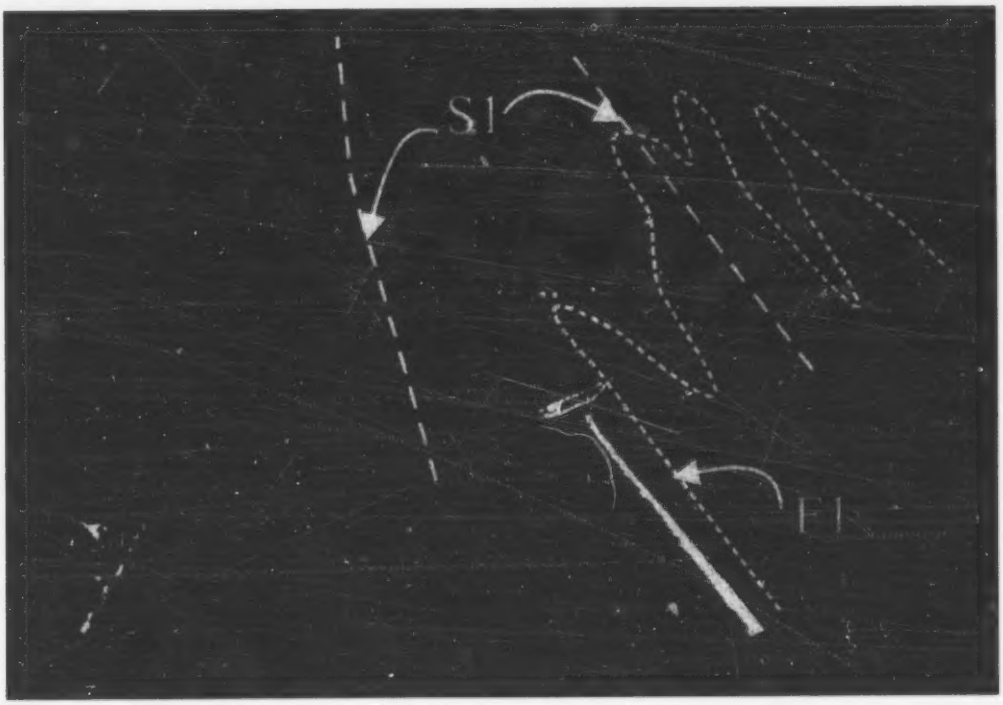


Photo 16. F_1 fold traces are accentuated by compositional layering in staurolite-kyanite-garnet-muscovite schist unit. The axial plane of the F_1 fold is parallel to subparallel with respect to the S_1 foliation. Transitional Zone, outcrop 3112. Hammer handle is 35 cm long.

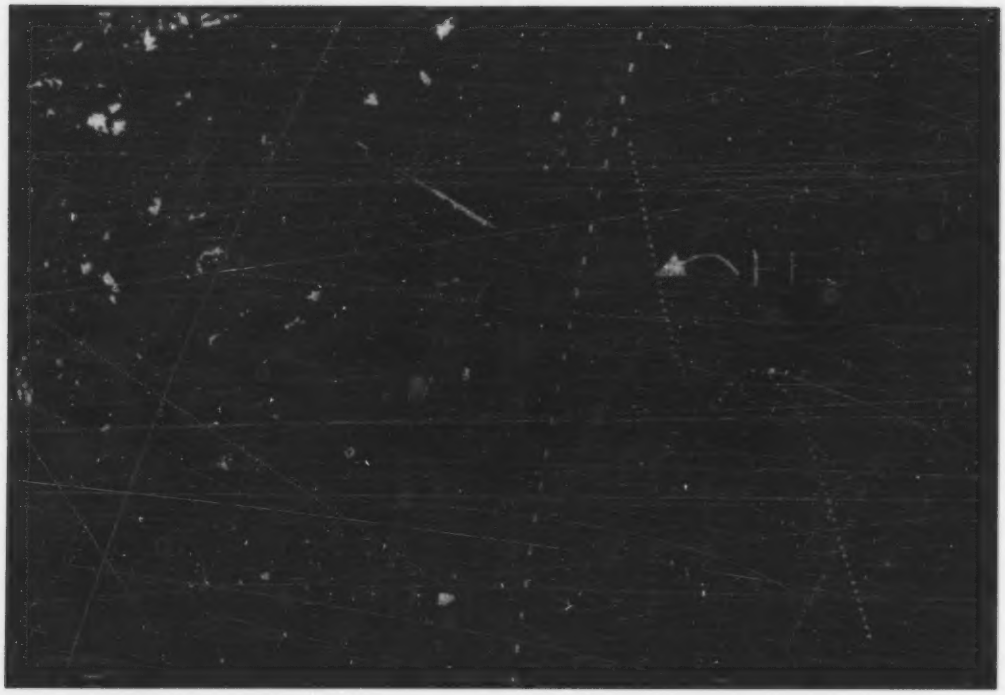


Photo 17. Sharp contact between a garnet-amphibolite dike (left) and host metapelite (right). Dike emplacement postdates F_1 folding. Transitional Zone, outcrop 3031. Pen is 14 cm long.

Photo 18. Close-up of the garnet-amphibolite metadike shown in Photo 17. Note the cross-like shape of garnet porphyroblasts. Transitional Zone, outcrop 3013. Pen is 14 cm long.

Garnet is common, but its quantity varies considerably, even on an outcrop scale. In places, for instance, garnet may constitute more than 40% of the rock. The garnet is brownish red in colour and commonly 1 to 7 mm in diameter. In a few places, however, garnet reaches diameters of greater than 2.5 cm. Garnet shows both syntectonic pressure shadows and posttectonic characteristics.

These gneisses are migmatitic. The leucosome consists of quartz and feldspar and usually forms discontinuous, boudinaged thin layers, elongated in the foliation plane up to 10 cm wide and twice as long (Photo 20). In places, garnet-biotite gneiss contains 5 to 7 cm diameter porphyroblasts of feldspar elongated in the plane of the foliation (Photo 21). Typically, the leucosome appears to be restricted to specific layers within the gneiss. There are two generations of granitic pegmatites within this unit. One is structurally parallel to leucosomes described above and may be similar in age and origin to them (Photo 20). They are commonly boudinaged and locally protomylonitic. The other generation is younger and cuts banding in the gneisses at a high angle (Photo 22).

There are discontinuous lenses of fine- to medium-grained foliated garnet-amphibolite layers 0.5 to 2 m wide within this unit (Photo 23). These amphibolite layers are conformable to the foliation plane and banding in the gneisses and may be thin dikes equivalent in age to the Nipissing gabbro dikes that occur in the schistose rock units on the north side of the Grenville Front boundary fault.

Garnet-muscovite gneiss unit

The garnet-muscovite gneisses typically occur as (200 by 40 m) lensoidal shaped bodies throughout the map area. The unit is heterogeneous, well banded and foliated, medium to coarse grained, and light brownish-grey in colour. The compositional variation in this unit is similar to that described for the garnet-staurolite-muscovite schist unit. Homogeneous quartz-feldspar-rich bands probably represent sandstone beds, and the coarse-grained white-mica-rich layers probably represent mudstone protoliths (Photo 24). Garnet is present in varied amounts in this unit; in general, it comprises 5% of the rock, but can be up to 30 to 40% in some layers.

Observations of folds (Photo 24) in this unit permit recognition of at least two stages of deformation. The first plane of folding (F_1) was concurrent with development of a strong foliation (S_1), which is parallel to the primary layering in the rock (S_0). The second plane of folding (F_2) does not have an associated penetration of a S_2 foliation (Photo 24).

Leucosome and an early generation of pegmatite occur conformable to the S_1 foliation and, presumably, are syn- to posttectonic with respect to D_1. Clearly, they are pre-D_2 (the second deformation), because they are deformed by the second stage of folding (F_2). The second generation of pegmatites truncates all of these deformed rocks (Photo 22).

Garnet-kyanite-muscovite gneiss unit

The kyanite-bearing unit occurs in a lens up to 30 m wide and 250 m long on the south side of the Grenville Front boundary fault along the contact between garnet-muscovite and garnet-amphibolite gneisses. The rocks are brownish-grey on the weathered surface and light grey on the fresh. The major constituents of this gneiss are quartz, feldspar, and muscovite with lesser biotite, garnet, kyanite and staurolite. The gneiss is generally coarse grained (Photo 25) with garnet porphyroblasts 2 to 5 mm in diameter and kyanite blades from 3 to 4 mm wide and 5 to 7 mm in length. Differential banding is not apparent within kyanite bearing gneiss. Leucosome is present but not abundant and there are a few boudinaged quartz veins parallel to the 060° striking gneissic foliation.

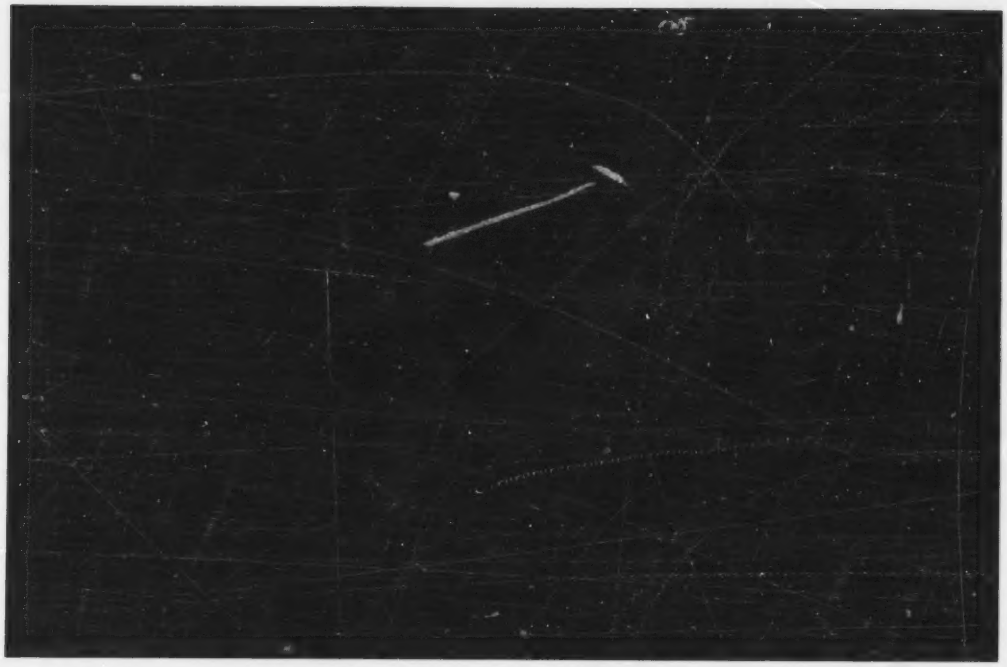


Photo 19. Compositional layering (possible transposed bedding) in garnet-biotite gneiss within the Grenville Province, outcrop 3020. Hammer handle is 35 cm long.

Photo 20. Leucosome layering developed in migmatitic gneisses within the Grenville Province (left). Pegmatitic dike (right) is oriented parallel to the S_1 foliation; outcrop 3020. Hammer handle is 35 long.

Photo 21. Feldspar aggregates in garnet-biotite gneiss are elongated in the plane of the S_1 foliation. Grenville Province, outcrop 3021. Pen is 14 cm long.

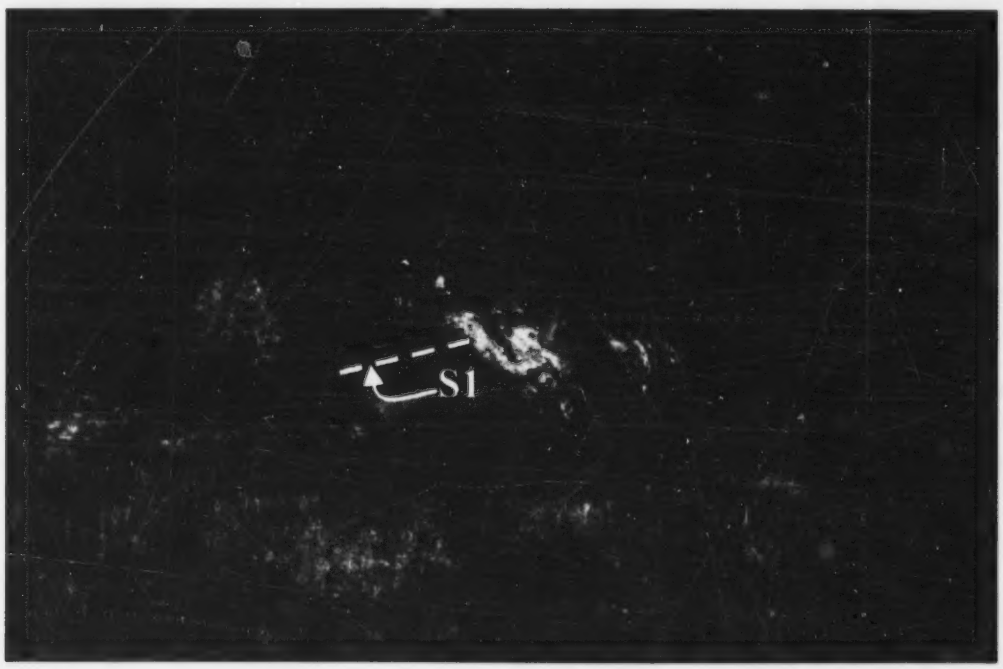


Photo 22. Late pegmatite vein within the Grenville Province cuts the S_1 foliation at a high angle. Outcrop 3024.

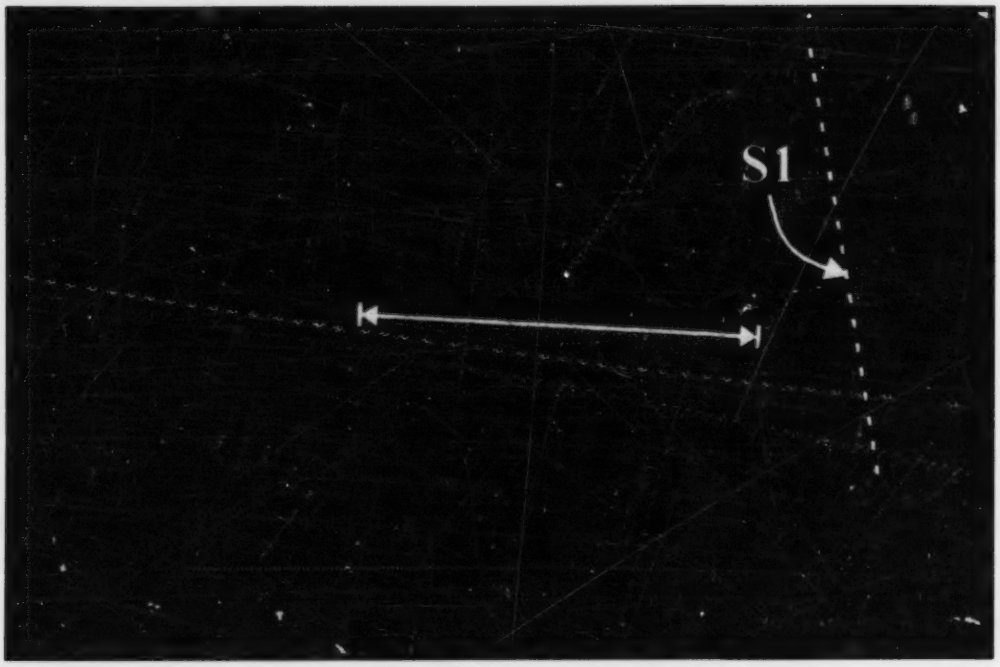


Photo 23. A garnet-amphibolite layer within garnet-biotite gneiss is parallel to the S_1 foliation. This may be a conformable dike or layering was transposed prior to formation of the S_1 fabric. Grenville Province, outcrop 3020. Pen is 14 cm long.

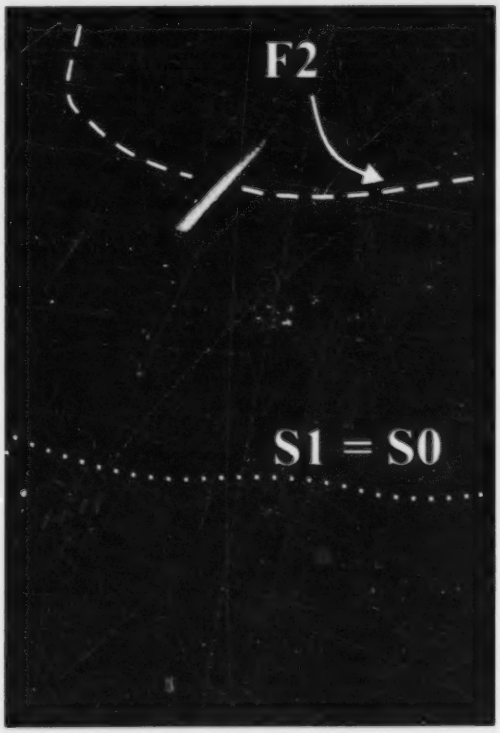


Photo 24. Interlayered metapelitic gneiss is moderately to tightly folded (F_2). Leucosome is parallel to the S_1 foliation. Grenville Province, outcrop 3020. Hammer handle is 35 cm long.

Garnet-amphibolite gneiss unit

This unit varies from homogeneous varieties, consisting largely of plagioclase and amphibole, to delicately banded types with layers rich in biotite, feldspar and quartz. Garnet is present in all of these rocks and, in rare cases, may constitute up to half of the modal mineralogy; idioblastic garnet crystals up to 5 cm in diameter are typical. Most of the amphibolites are probably derived from the volcanic rocks such as flows and tuffs. Rocks of this unit are foliated and well folded (Photo 26).

Rocks that form this unit are also migmatitic and impregnated with quartz-feldspar rich leucosome. The leucosomes occur as thin lenses and ribbons conformable to the gneissosity, so that the rock has a strongly streaked appearance (Photo 27). The same varieties of pegmatites that are associated with the garnet-biotite gneiss occur in these rocks.

Pegmatite unit

The constituent minerals of two generations of pegmatites are quartz, feldspar, muscovite, biotite and a minor amphibole. The development of folded granitic leucosome and first generation of deformed pegmatites occurred at 995 ± 3 Ma (Corfu and Easton, in press). Late, very coarse-grained, undeformed granitic pegmatites crosscut (azimuth 020°) the foliation within various migmatitic gneisses south of the Grenville Front boundary fault. South of the study area, these pegmatites were dated at 989 ± 2 Ma (Corfu and Easton, in press).

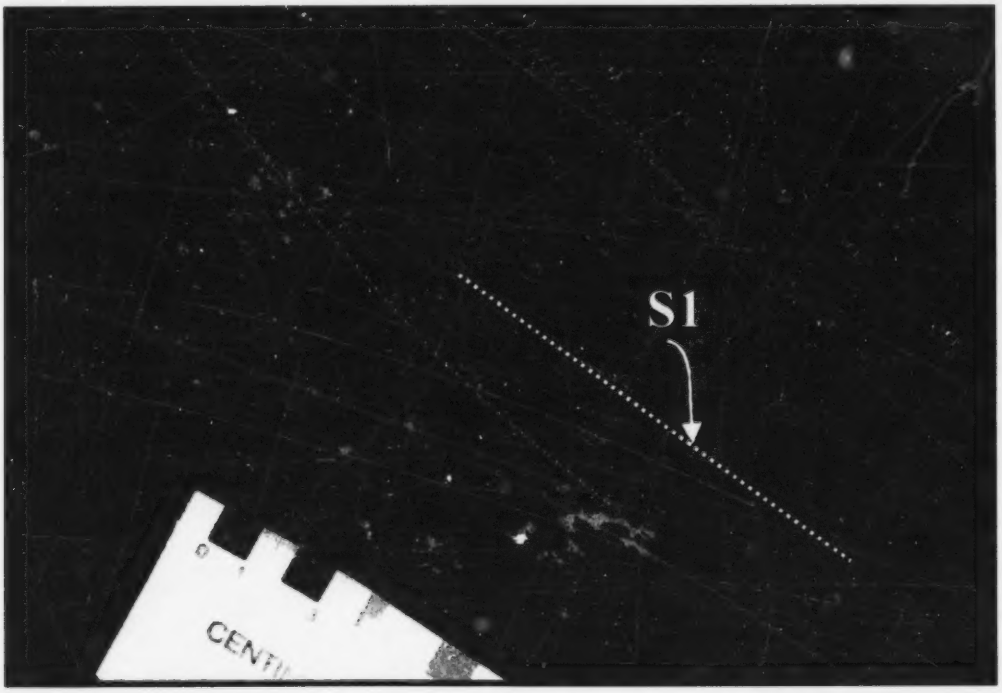


Photo 25. Coarse-grained garnet-kyanite gneiss with poorly developed S_1 foliation. Grenville Province, outcrop 3024.

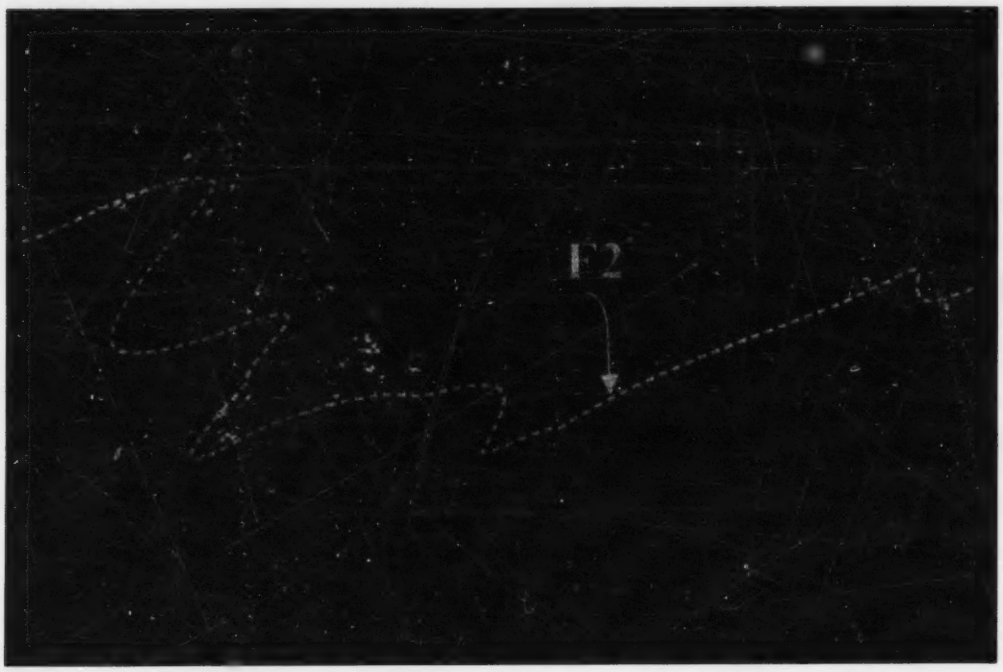


Photo 26. Leucosome emphasizes folding in garnet-amphibolite gneiss. Grenville Province, outcrop 3074. Hammer handle is 35 cm long.

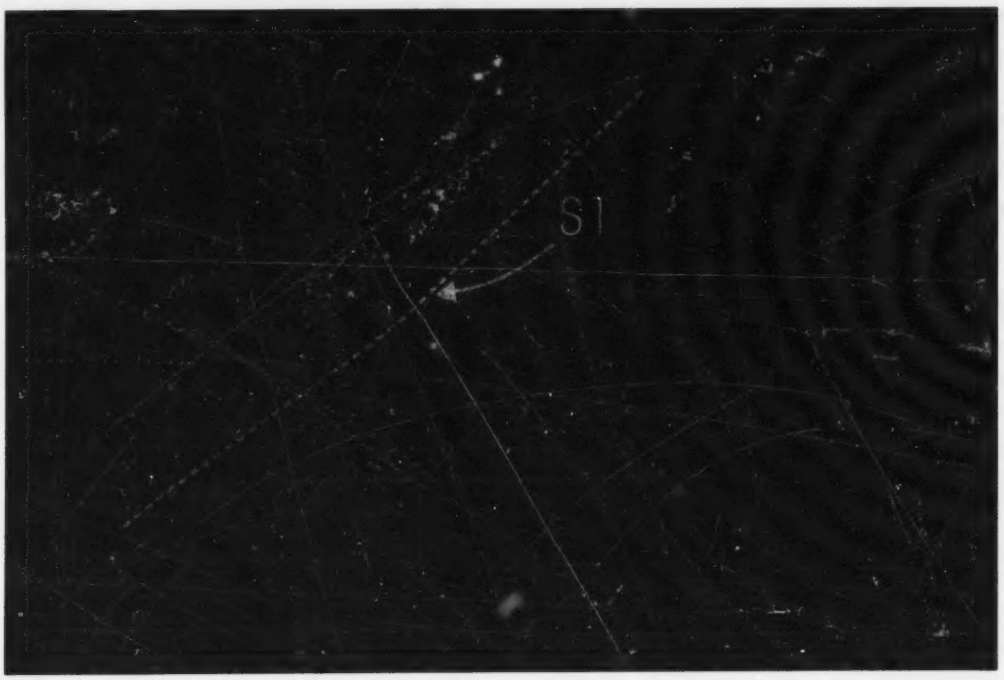


Photo 27. Variably flattened, thin leucosome layers and ribbons give this gneiss a streaked appearance. Grenville Province, outcrop 3027. Hammer handle is 35 cm long.

ROCK UNITS THAT STRADDLE THE GRENVILLE FRONT BOUNDARY FAULT

Nipissing Metagabbro

Nipissing metagabbro occurs throughout the study area (Figure 6) as bodies ranging from large irregular shaped masses to small dikes, and on both sides of the Grenville Front boundary fault (Lumbers 1973). The largest body of Nipissing metagabbro in the area appears to be both concordant and crosscutting with respect to the metasedimentary and metavolcanic rocks of the Transition Zone and granitic gneiss on the south side of the Grenville Front boundary fault. Contacts with adjacent units are not exposed. The rock of this unit is not migmatitic on the north side of the Grenville Front boundary fault and is almost leucosome free to the south of it. Rocks of this unit have a pseudodiabasic texture.

The rocks are generally medium grained, homogeneous and well foliated. Three varieties of the Nipissing metagabbro are recognized in the map area: mafic, felsic and porphyroblastic. All of them are composed of varied amounts of amphibole, plagioclase, and smaller amounts of quartz, biotite and accessory minerals. Garnet is not a common mineral within the Nipissing metagabbro, but locally may compose 1% to greater than 2% of the rock. The most abundant type is mafic Nipissing metagabbro mainly composed of 60% amphibole and 40% plagioclase. In contrast, the felsic Nipissing metagabbro occurs adjacent to the trace of the Grenville Front boundary fault and within the large body of more mafic amphibolite. These rocks are strongly foliated and contain higher proportion of feldspar, epidote and biotite with local hematite alteration. Porphyroblastic Nipissing metagabbro occurs locally (outcrop 3084, map P.3428 in back pocket) and contains pyroxene porphyroblasts as large as 0.7 to 1 cm in diameter. The matrix that encloses the porphyroblasts defines the regional foliation and is oriented at 060°/070°SE.

Unsubdivided Metagranite

Granitic rocks occur as 0.5 km wide northeast-striking zone though the central part of the study area (Figure 6). Foliated granite-granitic schists occur on the north side of the Grenville Front boundary fault, whereas on its south side, banded migmatitic granite gneiss dominates. Contacts with adjacent units are normally concealed, but, on outcrop 3163 (south side of the Grenville Front boundary fault), there is an exposure of a folded contact between granite gneiss and the garnet-biotite gneiss.

The granitic gneiss is fine to medium grained, pinkish-grey, and weathers pink. A compositional layering that is millimetres to centimetres thick and that has the appearance of primary magmatic layering (S_0) on the weathered surfaces is observed in many outcrops. In hand specimens, feldspar constitutes 35 to 50% and quartz as much as 45% of the rock. Dark coloured minerals are biotite and hornblende, and, in a few places, dodecahedral crystals of garnet up to 0.7 cm in diameter. The foliated granite-granitic schist that represents this unit on the north side of the Grenville Front boundary fault is foliated and homogeneous; it contains no migmatititic material or pegmatite. Leucosome and two generations of pegmatite dikes are commonly found in the granitic gneisses south of the Grenville Front boundary fault. The leucosome and older generation of pegmatites strike parallel to the foliation, where as second generation of pegmatites transect the foliation (Photo 28). This pattern is similar to that observed in garnet-biotite, garnet-amphibolite and garnet-muscovite gneisses.

Granitic rocks on the both sides of the Grenville Front boundary fault have a similar mineral and chemical composition. Geochemically, foliated granite and granitic gneisses are also very similar (*see* "Geochemistry"). These rocks are thought to be a part of the same granitic body, but with a different metamorphic overprint north and south of the Grenville Front boundary fault.

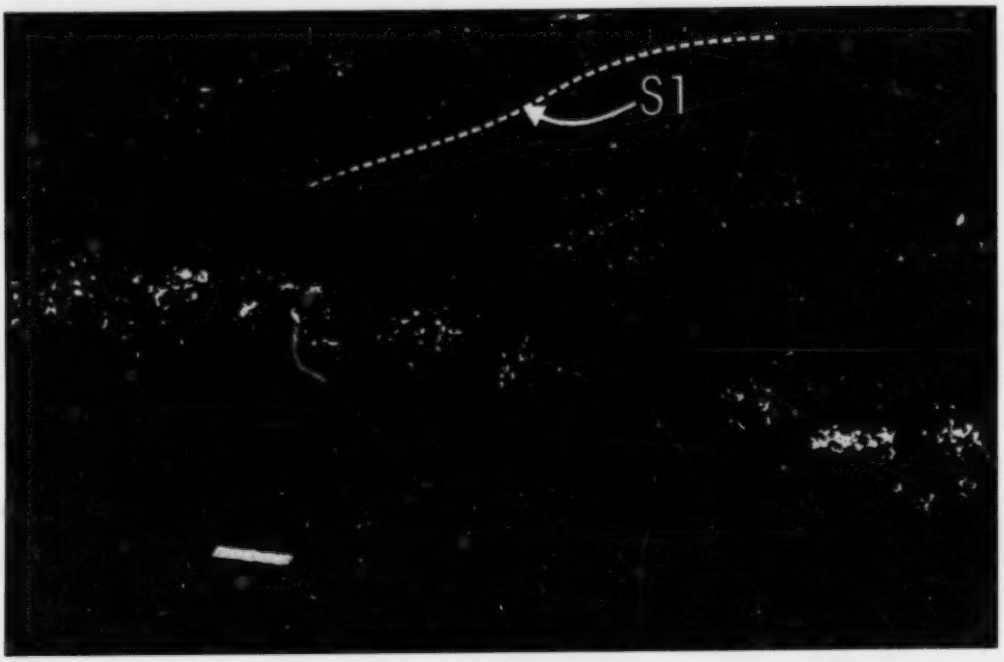


Photo 28. Leucosome lenses are elongated parallel to the S_1 foliation within the granitic gneiss unit. A late pegmatite veins crosscuts the S_1 foliation. Grenville Province, outcrop 3026. Hammer handle is 35 cm long.

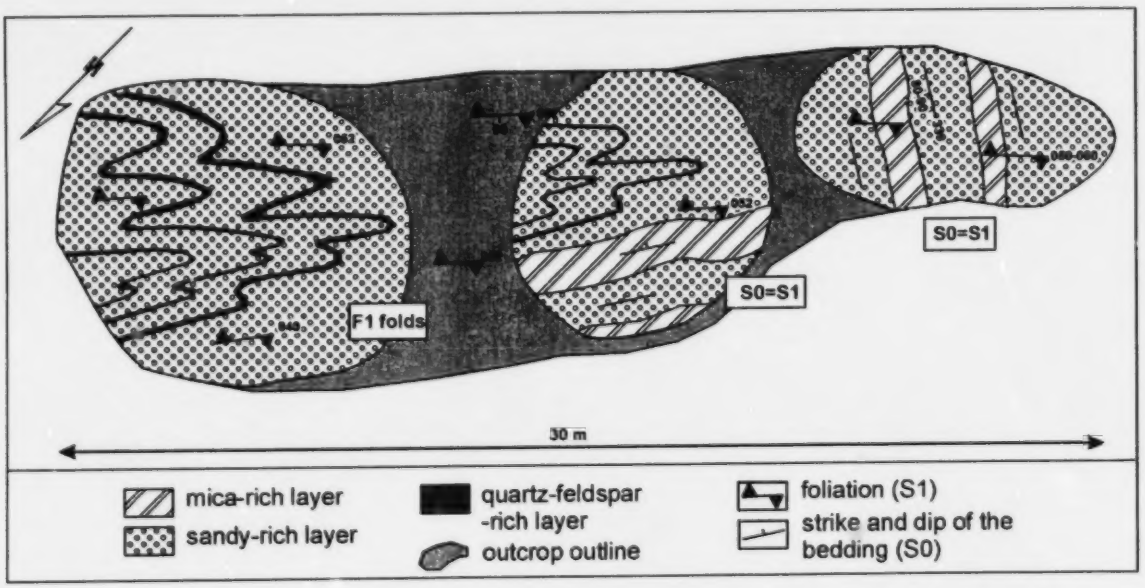


Figure 7. Relationship between bedding (S_0) and foliation (S_1) on an outcrop scale (outcrop 3112) in the Transitional Zone, Timmins Creek area.

STRUCTURAL GEOLOGY

Introduction

Structural data obtained during the field mapping is plotted on the 1:4000 scale geological map of the Timmins Creek area (map P.3428, back pocket). The attitudes of beds in the sedimentary formations as well as the schistosity and gneissosity in metamorphic rocks are indicated. The mapped and inferred boundaries of formations along with the location of faults and fold axes show the interpretation of the structure. Possible evidence of faulting, shearing, and tectonic brecciation is also documented. The most significant structural and/or metamorphic feature in the map area is the abrupt increase in deformation and metamorphic grade, from north to south across the Grenville Front (Ess Creek fault).

Folding

The Southern Province strata have been gently folded into an anticlinorium with a northeast striking axial plane. The study area (Figure 6) includes only the southeastern limb of this anticlinorium which locally exhibits well-formed S-shape drag folds (Photo 1). Adjacent to the Ess Creek fault, the axial plane of drag folds strike at 050° and dip 70°SE; the fold axis plunges 34°SW.

At the southeast boundary of the Southern Province, Mississagi quartzite and Bruce conglomerate, metamorphosed to lower greenschist facies, are cut by the Ess Creek fault. They are juxtaposed against schistose rocks of the Transitional Zone that were metamorphosed at medium amphibolite facies conditions. The complexity of structures increases dramatically within the Transitional Zone. The most prevalent foliation strikes at 060° and dips at 70°SE, which is parallel to the Grenville Front boundary fault and the Ess Creek fault. All metavolcanic and metasedimentary rocks within this zone contain tight (F_1) folds with axial planes striking at 050° to 060° and dipping at 60° to 70°SE. Folding (F_1) is well developed within the garnet-biotite and staurolite-garnet-muscovite±kyanite schists (Photo 16) and is best defined by quartz-feldspar layers or veins within more homogeneous, originally sandy units.

Figure 7 demonstrates the relationship between first stage deformation (F_1) and the two structural elements: bedding (S_0) and foliation (S_1). On the limbs of F_1 folds, primary bedding is parallel to subparallel to the foliation (S_1) but, in fold noses, they are crosscutting.

In the southeastern part of the Transitional Zone, these schistose rocks are truncated by the Grenville Front boundary fault. The contact between the schists and the Grenville Front boundary fault is not directly exposed. South of the Grenville Front boundary fault, well-banded migmatitic gneisses occur which exhibit concordant and discordant pegmatites of two generations. These gneisses exhibit tight to isoclinal F_2 folds with axial plane oriented 074°/70°SE and plunging at 45°SW. Their attitude is identical to that of F_1 folds in the Transitional Zone. Figure 8 illustrates schematically the relationship between the S_1 foliation (assumed to be the same as that in the Transitional Zone), F_2 folds, and pre- and post-F_2 migmatites and pegmatites. This migmatitic assemblage represents the peak metamorphic conditions during F_1 deformation in the study area. F_2 folds do not have an associated S_2 fabric indicating there was no new growth of metamorphic phases during this folding event. The simplest explanation for this phenomenon is that these F_2 folds formed as a result of the very ductile nature of the metamorphic environment attained during the F_1 event. In short, only one major metamorphic period is recognized. The geochronology data and cooling history presented in a subsequent section are consistent with this interpretation.

Faulting

There are two main trends of faulting in the map-area (Figure 9). The first one is a prominent system of faults striking at 070° across the central and southern part of the study area and the second is a system of more northerly trending faults with strikes at 020°. The first system includes the Ess Creek fault (or the Grenville Front) and the Grenville Front boundary fault (Figure 9). The second system includes the north-trending fault which truncates the Grenville Front in the central segment of the Street Township (Easton 1996) (Figure 5).

The Ess Creek fault (Grenville Front) follows a topographic lineament that is recognized over a strike length of 80 km between Crerar and north of River Valley. Previous studies (e.g., Thomson and Card 1963) have established that it is reverse fault, south side up and dips 60 to 80°SE; these data are based on outcrop and drill core descriptions. In an approximately 100 m wide zone where the trace of the fault is located "white mica schist" and "mafic metavolcanic rock" units show a strong foliation as a result of the ductile deformation. Late, minor, narrow brittle microfaults displace complex fold patterns due to early ductile deformation. If the Transitional Zone's metavolcanic and metasedimentary rocks on the south side of this fault represent the Stobie Formation (of the Huronian Supergroup), then uplift on the order of 10 km is indicated across the Ess Creek fault (Grenville Front). As well, rocks on the either side of the Ess Creek fault (Grenville Front) exhibit very different metamorphic conditions (*see* "Thermobarometry"). Rocks within the Transitional Zone have been recrystallized at depths in the range of 25 km, whereas Huronian strata have not exceeded 14 km. These data are similar to that reported by Zolnai et al. (1984) for Murray fault zone with tectonic relief estimated to be 10 to 15 km in the southeastern Southern Province.

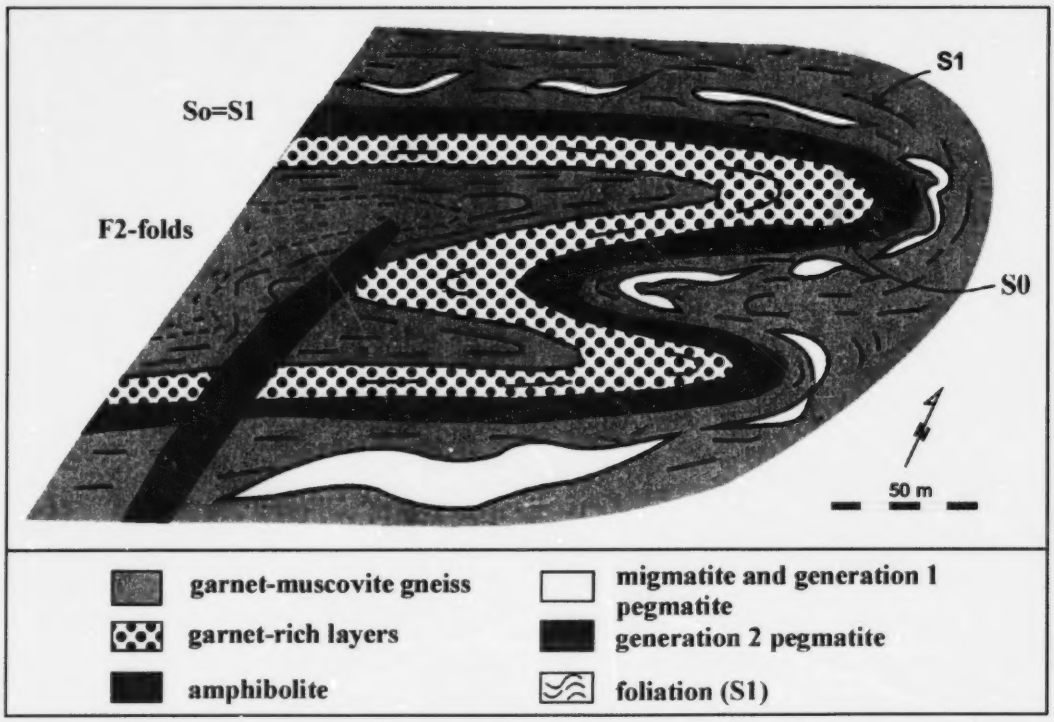


Figure 8. Relationship between F_1 and F_2 folds and migmatite and pegmatite formation, Grenville Province, Timmins Creek area.

Thomson and Card (1963) mapped a strongly developed southeast-striking schistosity along the Ess Creek fault that dips at 60 to 80°SE. They suggest that the absence of the Mississagi Formation strata on the south side of this fault is the result of erosion as a result of "south side up" displacement on the fault. The re-appearance of Huronian metavolcanic rocks at elevated metamorphic grade described by Easton et al. (1996) south of the Ess Creek fault is due to the same proposed displacement along the Murray fault. This similarity suggests that the Ess Creek fault is the eastward extension of the Murray and Wanapitei faults.

The Grenville Front boundary fault separates recrystallized and migmatized gneissic rocks of the Grenville Province from recrystallized schistose rocks of the Transitional Zone. This fault forms a northeast-striking zone 10 to 20 km in width and can be traced discontinuously across the entire map area. Unlike the Ess Creek fault, it does not have a strong topographic expression. Rocks within the Grenville Front boundary fault exhibit features typical of common gouge faults and widely distributed hematitic

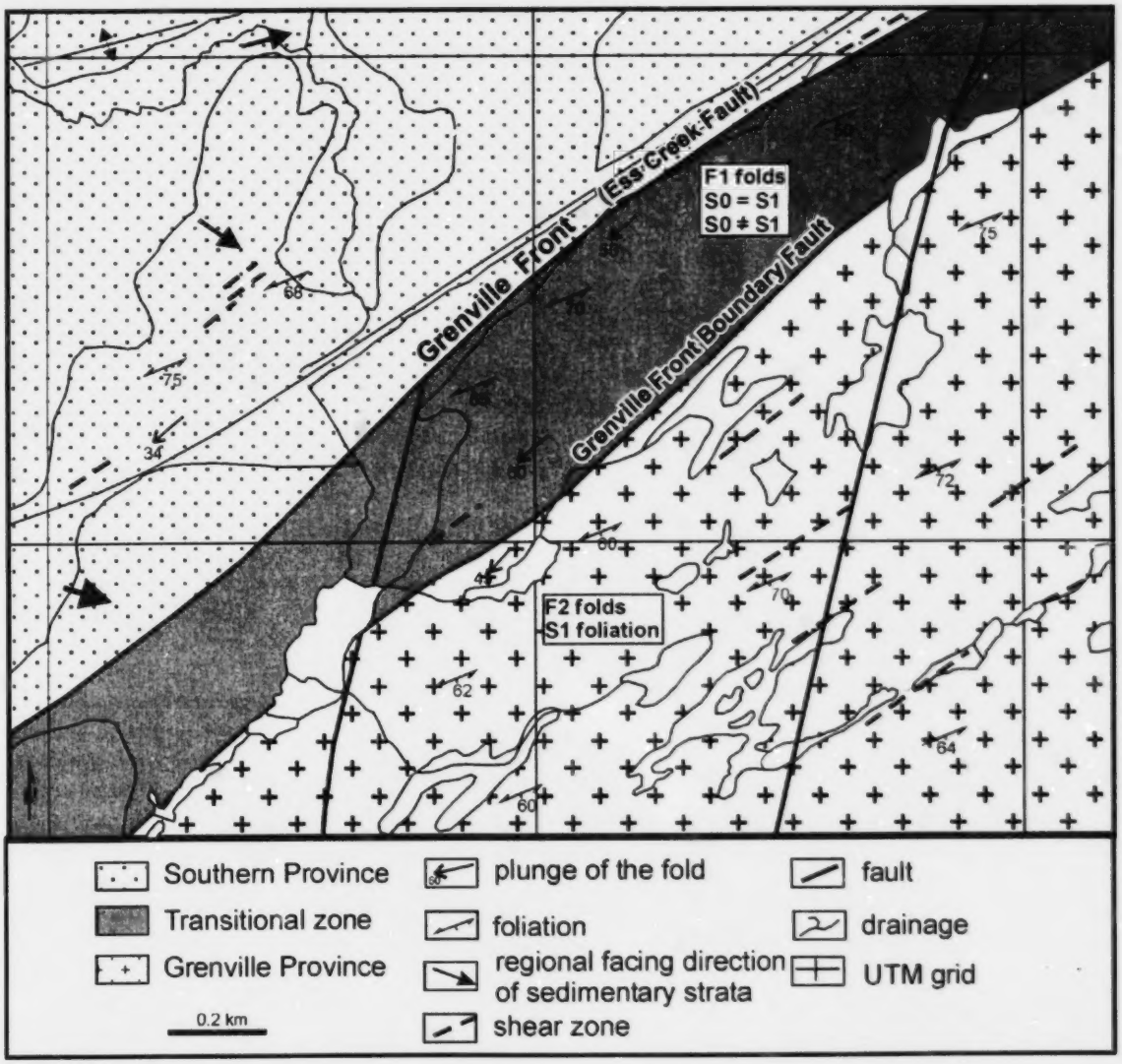


Figure 9. Structures in the Timmins Creek area.

staining (Photo 29). These features are consistent with brittle deformation and contrast with the ductile deformation typical of the Ess Creek fault (Grenville Front). Thermobarometry data presented in a subsequent section show that the maximum thrust displacement along the Grenville Front boundary fault is approximately 3 km.

In Street Township, the central segment of the Grenville Front is a north-trending, post-Grenville fault (Easton et al. 1996) (Figure 5). In the map area (Figure 6), several faults are parallel to this main structure. Some metasedimentary rocks in the Timmins Creek area (e.g., outcrop 3004-1) preserve a weak foliation that has the same orientation. The young pegmatite bodies (989 ± 2 Ma) in the central part of the map area (Figure 6) strike at 020°, and are believed to have been emplaced synchronous with these north-striking faults.

Local discontinuous zone of ductile deformation

In both the Mississagi and Bruce formations of the Southern Province, there are locally well-developed zones of ductile deformation and brecciation. Two types are recognized: 1) lozenge-shaped zones of Mississagi quartzite 10 centimetres to several metres long whose axis is parallel to the orientation of the foliation in a very schistose matrix (of similar composition); and 2) angular to subrounded fragments of Mississagi quartzite or Bruce conglomerate, centimetres to metres in length, with long axis near parallel to foliation in a clast-rich, schistose matrix. The author sees three possible ideas that can explain the origin and development of these structures.

1. Type 1 might represent compositional variation within a sedimentary unit, where sandy material is interlayered with more mudstone-rich material. As a result of deformation, a stronger foliation may develop in the less resistant mudstone-rich layers. This interpretation is supported by the similarities in mineralogy between the fragments and matrix.
2. A second explanation for type 1 structure is that it formed as local zones of intense ductile deformation related to Grenville Front deformation.
3. The brecciation within both the Mississagi and Bruce formations is similar to Sudbury Breccia, viz. blocks of host rock of all sizes within a fine-grained matrix of similar composition.

Several zones of ductile deformation within the Grenville Province and the Transitional Zone, which are parallel to the Grenville Front boundary fault, were documented in the map area and are illustrated in the Figure 9. In this direction, these rocks may exhibit a weak mylonitic fabric. At the microscopic scale, these rocks have brecciated clasts surrounded by a glassy matrix (Photo 30). No explanation is provided in this report for the development of these zones.

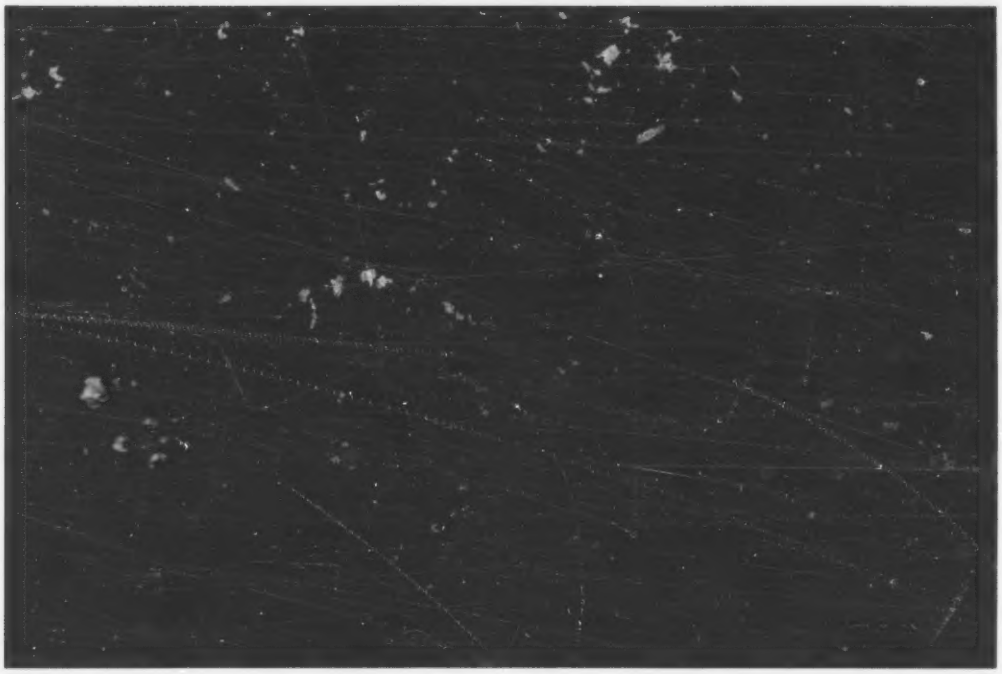


Photo 29. Strong hematitic staining and the development of fine-grained, chloritic fault gouge are common features found in the rocks located near the Grenville Front boundary fault. Outcrop 3019. Pen is 14 cm long.

Photo 30. Thin section under plain polarized light showing intense brecciation within a garnet-biotite schist. The sample is from a shear that parallels the Grenville Front boundary zone. Sample number 96rme-3015, Transitional Zone.

Petrology, Thermobarometry, Geochemistry and Geochronology

PETROLOGY

Southern Province

The grade of metamorphic rocks in this domain is low to middle greenschist facies. In pelitic rock compositions, white mica is present; in more psammitic rocks, chlorite is observed. Blue-green hornblende occurs in rocks of mafic composition supporting the observation that at least middle greenschist conditions have prevailed in this region.

Mississagi quartzite and Bruce metaconglomerate are the only Huronian units exposed in the study area. Mississagi quartzite occurs as massive to foliated varieties—both consist dominantly of quartz, plagioclase, lesser potassium feldspar, chlorite and white mica (Table 1). Massive types consists of medium- to coarse-grained, strained, relic clasts of quartz and feldspar, and an interstitial, fine-grained, chlorite-quartz-feldspar matrix (Photo 31). Foliated varieties exhibit a more advanced stage of recrystallization. They contain a higher proportion of the matrix assemblage which is coarser grained, and quartz and feldspar which occur as porphyroclasts (Photo 32). In these rocks, planar features (tectonic or shock metamorphism origin) in quartz are locally preserved, relict feldspar is variably altered to saussurite, and metamorphic plagioclase is albitic (An_{0-5}) in composition (Figure 10). Throughout the Mississagi quartzite in the study area, strongly foliated rocks occur on a very local scale within centimetre- to metre- wide shear and/or breccia zones described in a previous section. One sample of this material is shown in Photo 33 and its mineralogy is presented in Table 1a. Compared to less foliated varieties it is strongly foliated, white mica rich, and has considerably more (metamorphic) matrix (compare Photos 31 and 33).

Foliated Bruce conglomerate has a similar mineralogy to the Mississagi quartzite (Table 1a). The matrix in the Bruce conglomerate typically has abundant white mica (Photo 34). Clasts consist of quartz pebbles (80%) and plagioclase (20%). The texture and degree of recrystallization of this unit is similar to that of the Mississagi quartzite.

Sills of Nipissing gabbro in the study area show different degrees of metamorphic recrystallization. Rocks in the core of the sills typically have igneous textures and mineralogy with some accessory metamorphic biotite (Table 1a, Photo 35) and hornblende (Table 1a, Figure 16, Photo 35). Pyroxene comprises 45 to 50% of most samples (30 to 35% Cpx, 15% Opx). Composition of plagioclase ranges are An_{62-70} (Figure 10). In samples from the margin of the sills, the pyroxenes typically have discontinuous rims of blue-green hornblende or actinolite pseudomorphs. The fact that blue-green hornblende has formed here suggests these rocks are part of a low-pressure facies series, which is consistent with estimates of metamorphic grade in the Southern Province by Fox (1971) and Blonde (1996). Biotite in such rocks forms well-developed zones enclosing igneous iron oxide. Clinozoisite-epidote occurs as irregular aggregates in plagioclase grains, spatially associated with sericite alteration. Mineral phases, including biotite, amphibole, chlorite, sericite and epidote group minerals are in equilibrium in these rocks (Photo 35).

Table 1. Modal composition of some metapelites, metabasites and felsic meta-igneous rocks from the Timmins Creek area, Street Township.

A. Modal composition of metasediments and metabasites in the Southern Province.

Sample	rme-3001	rme-0017	rme-0016	rme-3002	rme-0610	rme-0609
Rock type	Mississagi quartzite, sheared	Mississagi quartzite, foliated	Mississagi quartzite, massive	Bruce conglomerate	Nipissing gabbro	Nipissing gabbro
blue-green hornblende					3-5%	5%
actinolite						45-50%
biotite					2-3%	2-5%
muscovite	5-10%	<5%	15-20%	10-15%		
K-feldspar		5-10%				
plagioclase	15-20%	35-40%	10-15%	15-20%	50%	45-50%
quartz	65-70%	50-55%	50-60%	65-70%	<5%	
epidote	2%	<2%	2-3%	1%	3-5%	5-7%
chlorite	5-7%	>2%	10-15%	5-10%		
opaque	2-3%	1-2%	<2%	1-3%	<2%	<3%

B. Modal composition of metapelitic rocks in the Transitional Zone.

Sample	rme-3040	rme-3005	rme-3032	rme-3006	rme-3015	rme-3031	rme-3112
Rock type	white mica schist	meta-conglomerate	meta-conglomerate	Grt-Bt schist	Grt-Bt mylonitic schist	Grt-Bt schist	Ky-St schist
amphibole		30-35%					
biotite		20-25%	20-30%	15-20%	5%	25-35%	25%
muscovite	5%		5%	10%	7-10%		5-10%
garnet		10-15%		5-10%	10-15%	5-7%	10-15%
K-feldspar					5%		
plagioclase	30-35%	20-30%	40%	55-65%	50-60%	40-50%	50-55%
quartz	60-65%	30-35%	60%	10-15%	10-15%	10-15%	30-40%
staurolite							5-7%
kyanite							1-2%
titanite		1-2%					<1%
epidote	<1%	<1%	<1%	<1%	<1%	<1%	<1%
chlorite	3-5%	<5%	<2%	3-5%	10%	1-2%	1%
rutile		1%					
opaque		~3%		1-2%	<5%	1-2%	1-2%

C. Modal composition of the mafic and felsic meta-igneous rocks within the Transitional Zone and Grenville Province.

	Transitional Zone					Grenville Province	
Sample	rme-3004	rme-3042	rme-0132	rme-3008	rme-3147	rme-3148	rme-3151
Rock type	mafic metavolcanic	felsic metavolcanic	mafic dike	granite schist	Nipissing gabbro	Nipissing gabbro	Nipissing gabbro
amphibole	65-70%	7-10%	50-55%	15-20%	55-60%	50-60%	45-55%
biotite	1-2%	15-20%	3-5%	10-15%			
muscovite						<3%	
garnet	in the veins		10%				
K-feldspar				10-15%			
plagioclase	25-30%	45-50%	25-30%	15-20%	35-40%	40-50%	40-50%
quartz	5-10%	35-45%	3-5%	15-20%			
staurolite							
kyanite							
titanite	3-5%	<3%	<2%	<5%		<3%	<2%
epidote		3-5%	1-2%	<3%	5-10%	5-7%	<5%
chlorite							
rutile							
opaque	<3%		1-2%	1-2%	<2%	<3%	<3%

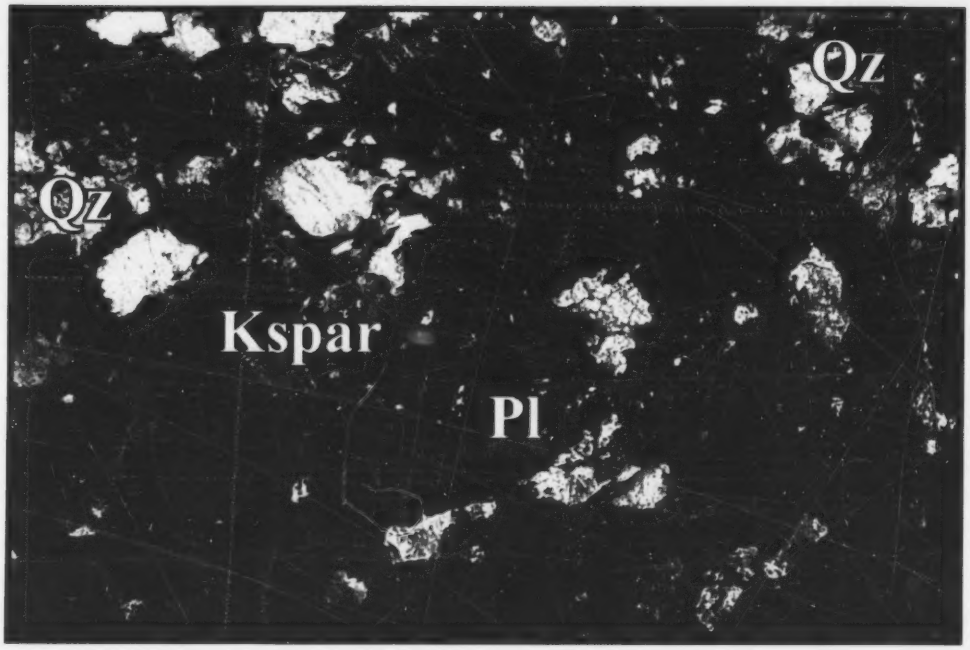


Photo 31. Crossed nicols, thin section view of massive quartzite of the Mississagi Formation. The sample consists of medium- to coarse-grained clasts of quartz (Qz) and feldspar (Kspar, Pl) in a fine-grained, chlorite-quartz-feldspar matrix. Field of view is 1.7 mm wide. Sample 96rme-3001, Southern Province.

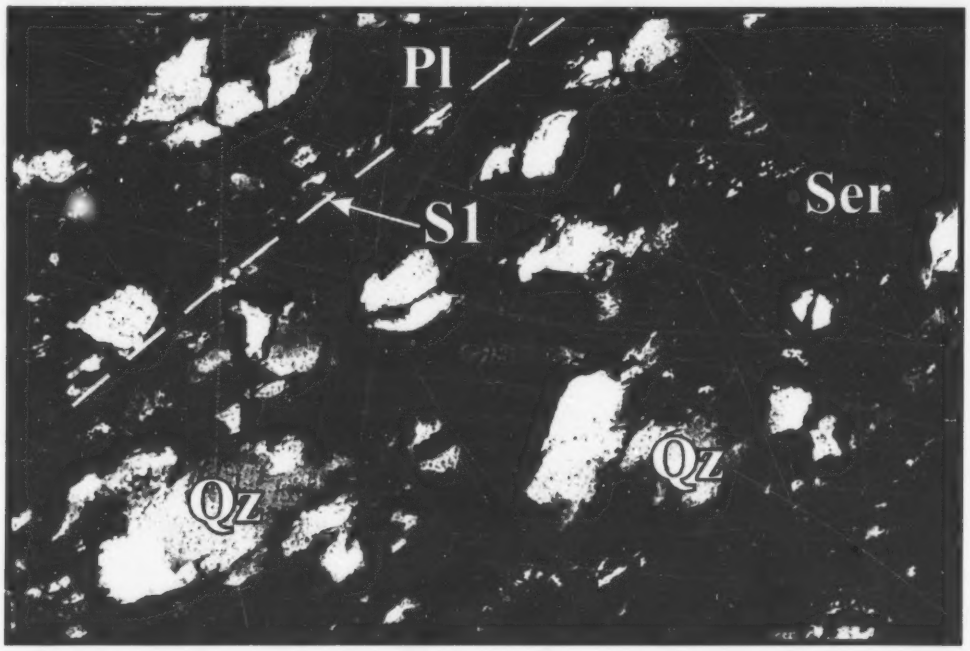


Photo 32. Crossed nicols, thin section view of foliated quartzite of the Mississagi Formation. The sample consists of quartz (Qz) and plagioclase (Pl) grains in a highly recrystallized matrix. Planar features in quartz are locally preserved, feldspar is variably altered to sericite (Ser). S1 denotes metamorphic foliation. Field of view is 1.7 mm wide. Sample 96rme-3001, Southern Province.

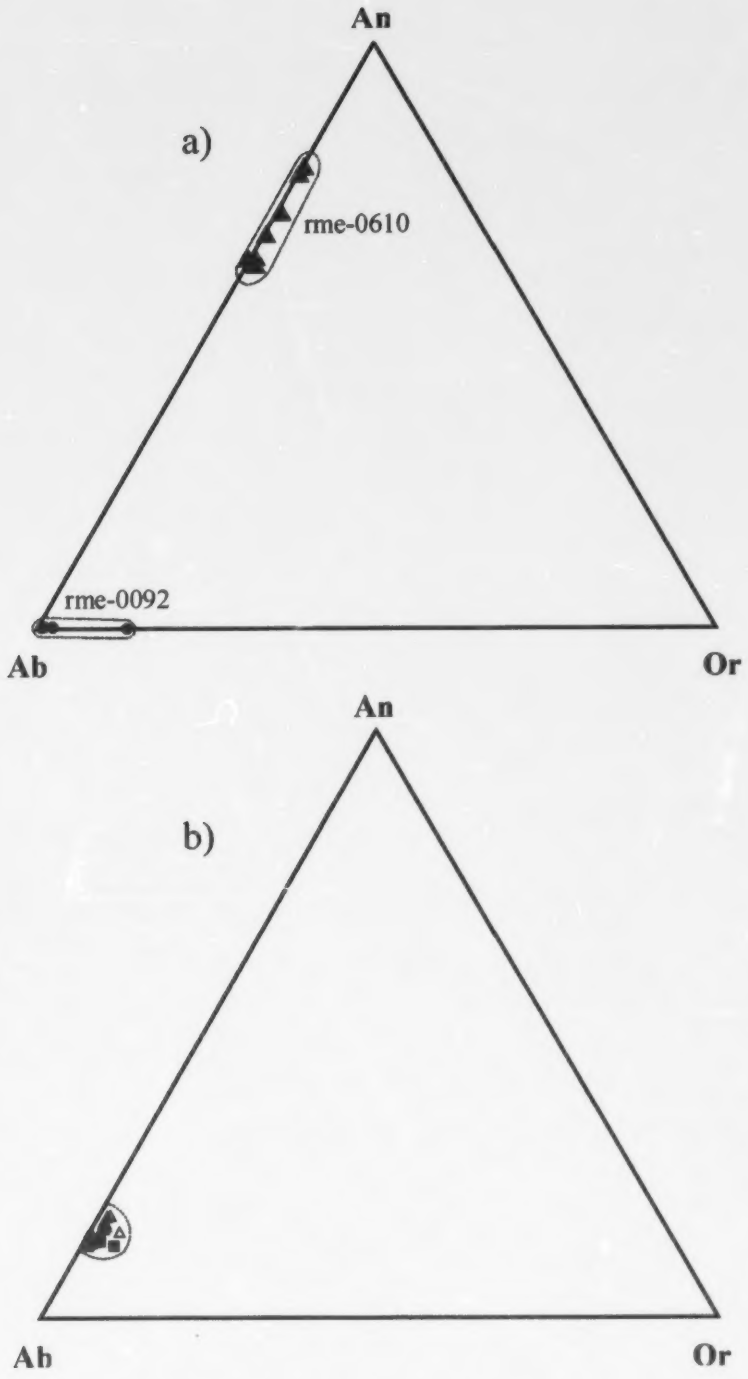


Figure 10. Composition of plagioclase in the ternary Ab-An-Or diagram for rocks from a) the Southern Province (samples rme-0092, rme-0610), and b) granitic rocks from both the Transitional Zone (sample rme-3008, ■) and the Grenville Province (sample rme-3022, Δ) in the Timmins Creek area.

Photo 33. Crossed nicols, thin section view of sheared quartzite (Mississagi Formation) has smaller clasts compared to less sheared varieties (compare with Photo 31). This rock is more micaceous, and has a lower clast to matrix ratio. Abbreviations: Musc, muscovite; Pl, plagioclase; Qz, quartz. Field of view is 1.7 mm wide. Sample 97rme-3016, Southern Province.

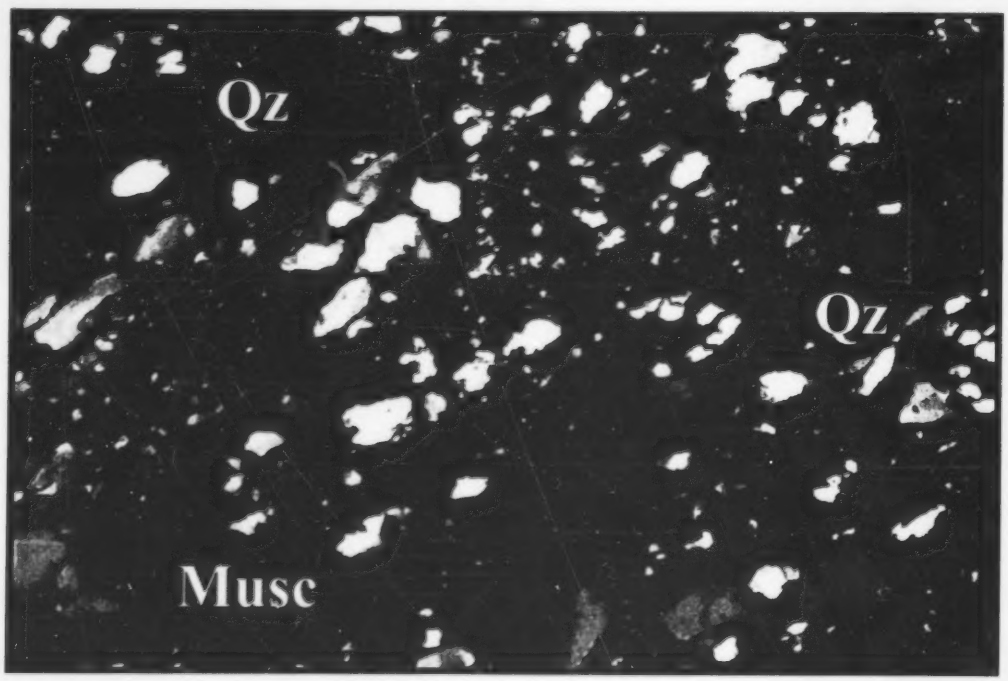


Photo 34. Crossed nicols, thin section view of foliated conglomerate of the Bruce Formation. The sample consists mainly of quartz grains (pebbles) in a micaceous matrix. Abbreviations: Musc, muscovite; Qz, quartz. Field of view is 1.7 mm wide). Sample 96rme-3002, Southern Province.

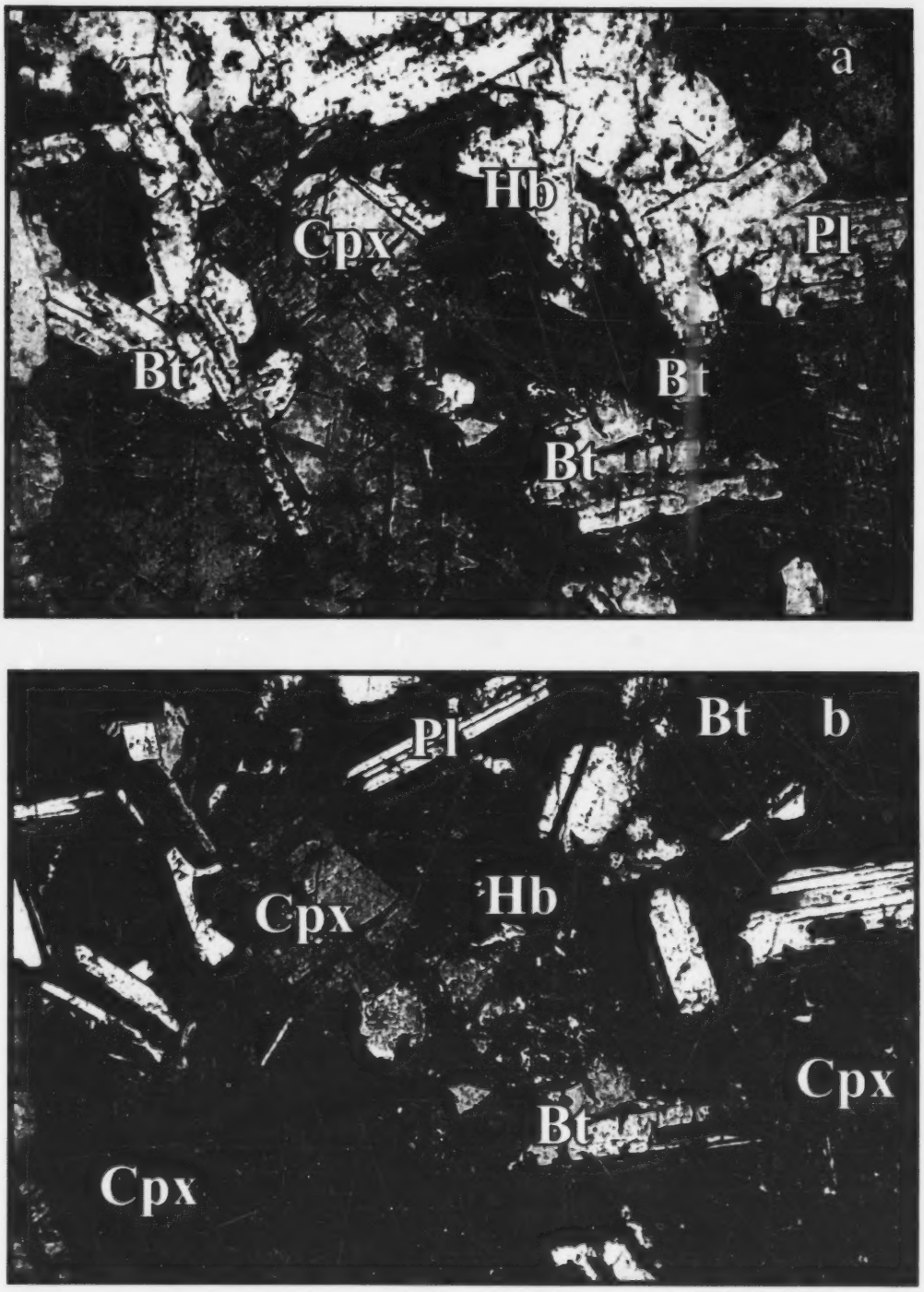


Photo 35. Crossed nicols, thin section view of a Nipissing gabbro exhibiting igneous texture and mineralogy with minor amounts of metamorphic biotite (Bt) and pseudomorphic actinolite and blue-green hornblende (Hb). Pyroxenes comprise 45 to 50% of the rock (30 to 35% Cpx, 15% Opx). a) Plane polarized light, b) crossed nicols. Field of view is 1.7 mm wide. Sample 96rme-0610, Southern Province.

Transitional Zone

The grade of metamorphic rocks in this domain is low to middle amphibolite facies. Pelitic rocks are garnet and staurolite bearing with trace amounts of kyanite. Recrystallized dark-green hornblende and lesser amounts of brown biotite are the major mafic minerals in the rocks of mafic and granitic composition. In general, the texture of these rocks may be described as lepidoblastic with poikiloblasts of garnet. The following descriptions of different varieties of rocks within the Transitional Zone have been subdivided into three major groups, which include rocks of plutonic, volcanic and sedimentary origin.

PELITIC ROCKS

Several units of pelitic composition occur within the map area (Figure 6). Foliated, medium- to coarse-grained schists are composed of quartz, plagioclase, muscovite, biotite, garnet, staurolite and trace kyanite with accessory amounts of ilmenite, titanite and rutile. Accessory amounts of secondary epidote is usually present after plagioclase, whereas chlorite mostly occurs as a retrograde phase after garnet and biotite (Table 1b, samples: rme-3005, rme-3006, rme-3015). The most abundant minerals are biotite, muscovite, quartz and plagioclase (An_{20-30}) (Table 1b, Figure 11).

The matrix of the metapelites is medium to coarse grained, foliated and micaceous. Both biotite and muscovite laths define the S_1 foliation plane (Photo 36). The composition of biotite within pelitic rocks is illustrated in Figure 12; Fe/Fe+Mg for this phase is shown to vary from 0.47 to 0.77 depending on the rock composition.

Garnet forms idioblastic porphyroblasts, most of which exhibit poikiloblastic textures. Some grains of garnet have cores with abundant fine-grained inclusions of plagioclase, quartz and opaque minerals and relatively inclusion free rims (Photo 37). Others are slightly elongate parallel to the S_1 foliation. These features and good crystal boundaries indicate syn- to postectonic growth of garnet (Photo 38). The garnets within metapelites are almandine-rich and show the compositional range $Al_{69-76}Gr_{4-16}Sp_{1-9}Py_{4-16}$ (Figure 13). Microprobe traverses across individual garnets from different pelitic units show some compositional variations, but most are fairly uniform with cores slightly enriched in Mg and depleted in Fe. A very few garnet grains (sample rme-3005) show a pronounced bell-shape distribution for MnO (Spess) (Figure 14), that probably records the progression of metamorphic conditions from greenschist to amphibolite facies during garnet growth (F. Ford, Geoscience Laboratories, personal communication, 1997, 1998). Compositionally, homogeneous garnets (sample rme-3112 (Figure 15)), which are typical in these rocks, indicate sustained growth under relatively constant temperature conditions (Spear 1993).

Both kyanite and staurolite, which are good metamorphic indicator minerals, are present in the pelitic rocks of this domain (Figure 6: samples: rme-3112 and rme-0242). Staurolite forms xenoblastic crystals that have sharp mineral boundaries with the muscovite-biotite-garnet assemblage (Photo 39). Kyanite occurs as individual subidioblastic blades, which are oriented parallel to the S_1 foliation (Photo 40). The assemblage kyanite-staurolite-garnet-biotite-muscovite-quartz-plagioclase is in textural equilibrium in these rocks and forms a syn- to post-F_1 fabric.

Collectively, the mineral parageneses in the Transitional Zone for rocks of semi-pelitic to pelitic composition indicate the area reached the staurolite-kyanite subfacies conditions of the amphibolite facies (Bucher and Frey 1994).

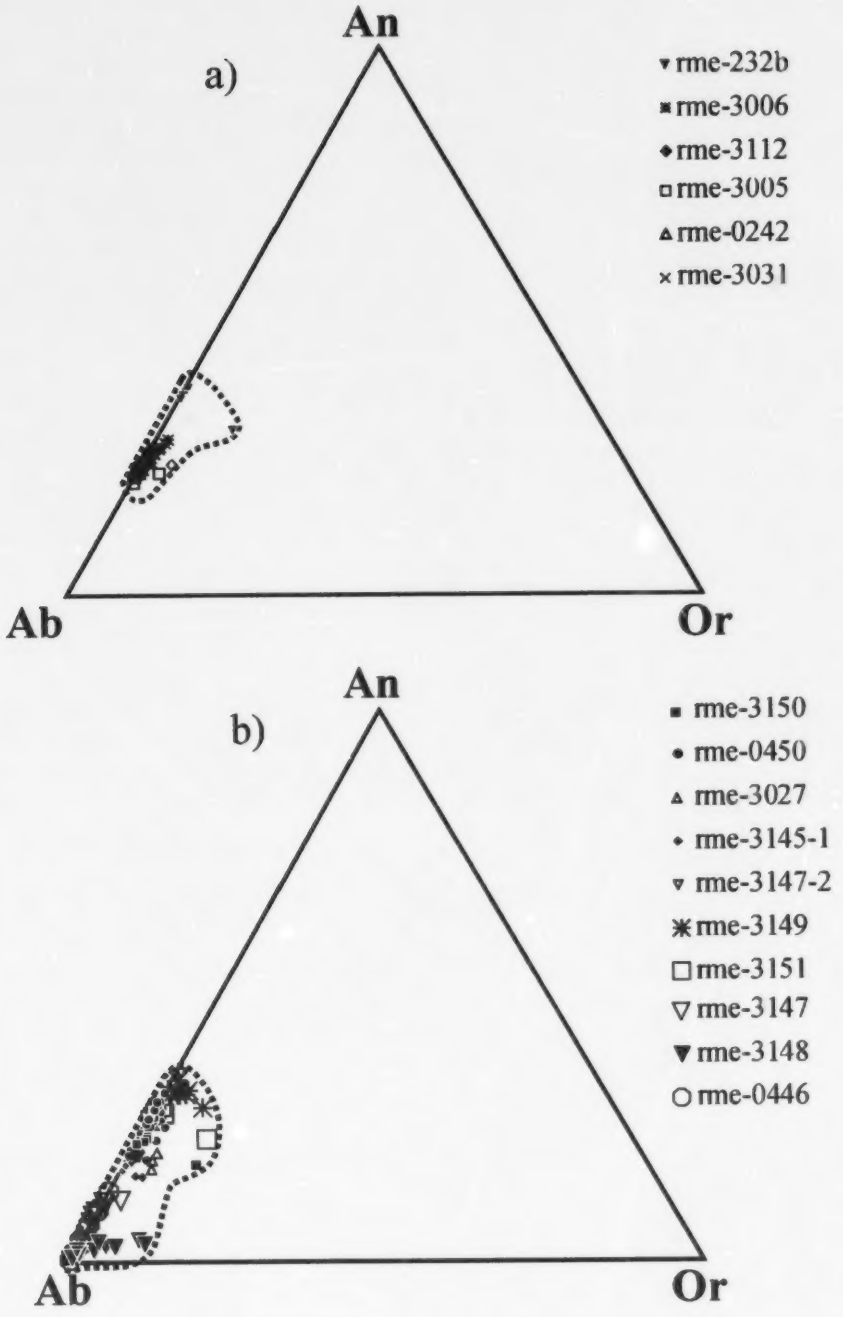


Figure 11. Compositional fields of plagioclase in the ternary Ab-An-Or diagram for a) metapelites, and b) metabasites in the Timmins Creek area.

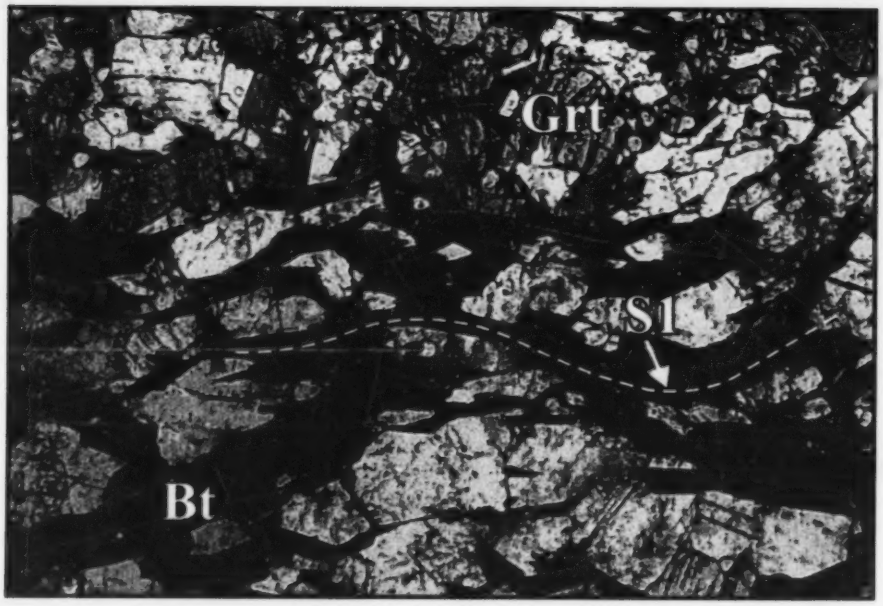


Photo 36. Thin section view of a medium- to coarse-grained garnet (Grt)-biotite (Bt) schist. Biotite laths define the S_1 metamorphic foliation. Field of view is 4.2 mm wide. Sample 96rme-3031, Southern Province.

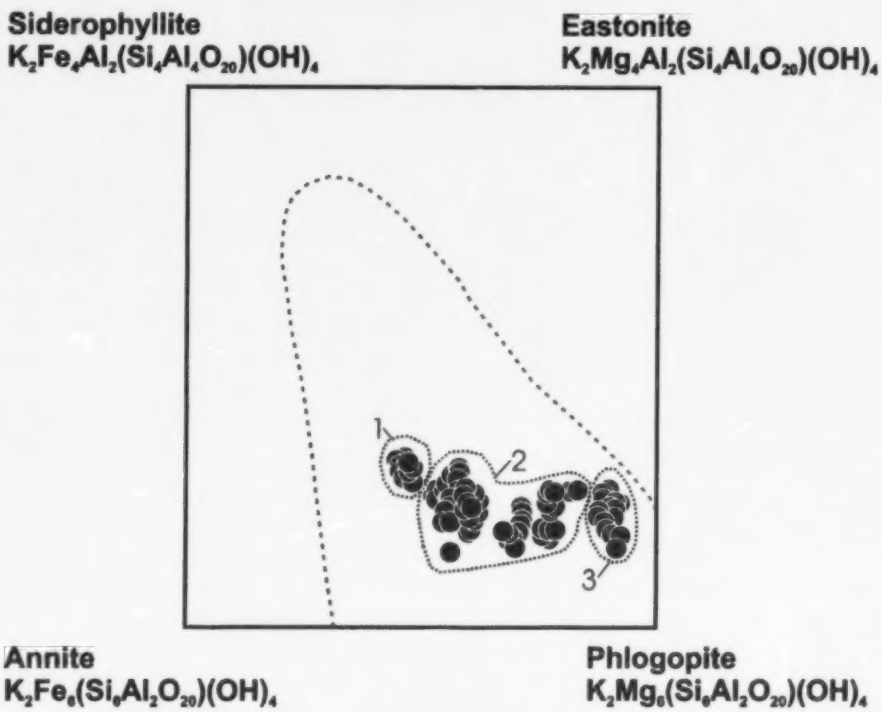


Figure 12. Biotite compositions from metapelitic, metabasic and granitic rocks, from both the Transitional Zone and the Grenville Province, in the Timmins Creek area (*after* Deer et al. 1992). Field 1 represents kyanite-staurolite-bearing metapelitic rocks (samples rme-0242 , rme-3112). Field 2 represents metapelitic and metabasitic rocks (samples rme-3151, rme-3149, rme-3031, rme-3020, rme-3015, rme-3005, rme-0450, rme-3027, rme-3006). Field 3 represents granitic rocks (samples rme-3022, rme-3008).

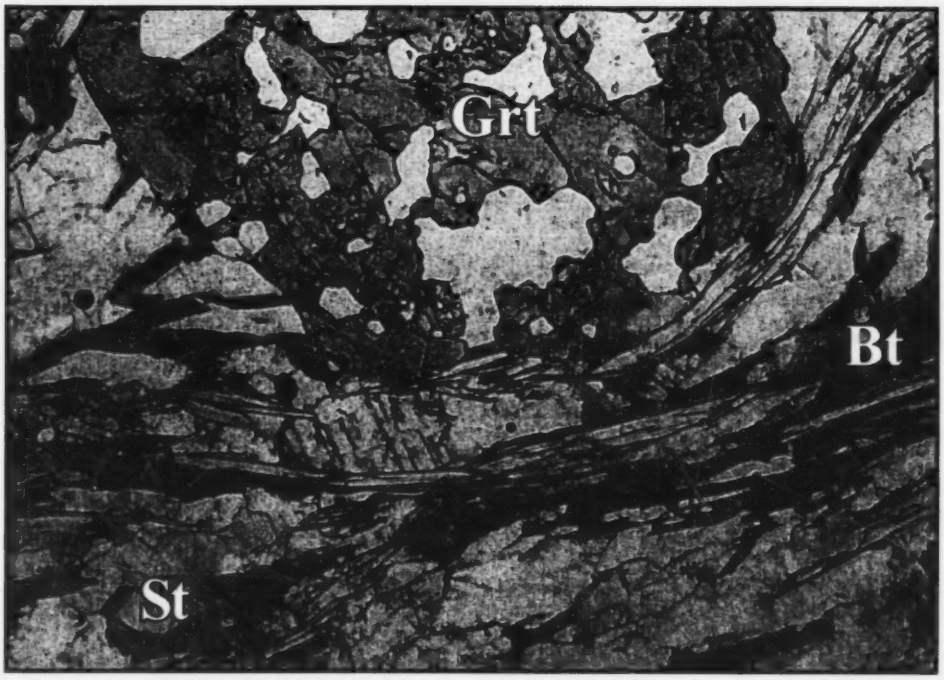


Photo 37. Thin section view of a coarse-grained kyanite-staurolite (St)-garnet (Grt)-biotite (Bt)-muscovite schist. Garnet porphyroblast shows poikiolitic texture with plagioclase and quartz inclusions in the core and inclusion-free rims. Field of view is 4.2 mm wide. Sample 96rme-3112, Transitional Zone.

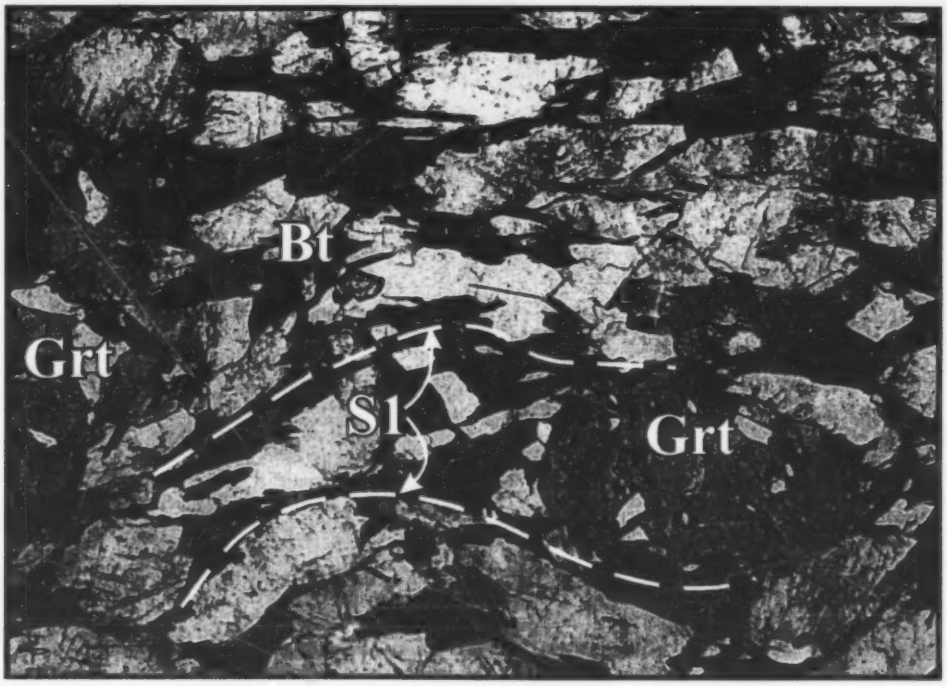
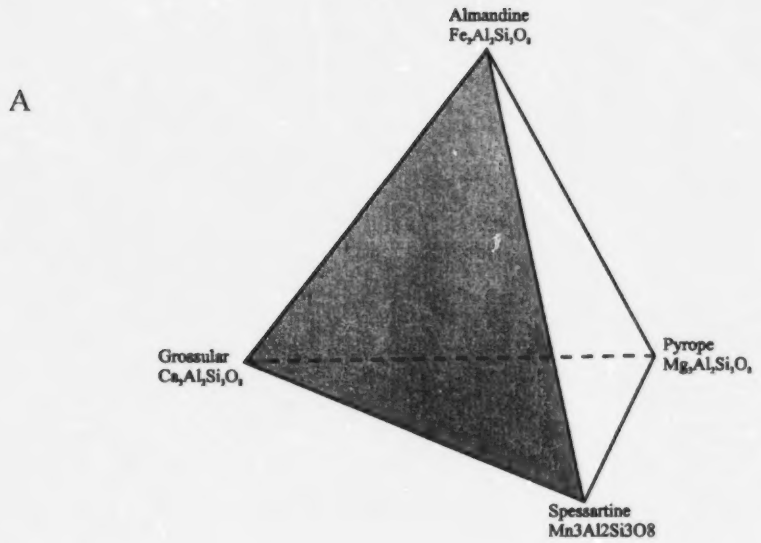


Photo 38. Thin section view of a garnet-biotite schist, with biotite (Bt) laths defining the S_1 foliation. Garnet (Grt) porphyroblasts show evidence for syn- to posttectonic growth. Field of view is 4.2 mm wide. Sample 96rme-3031, Transitional Zone.



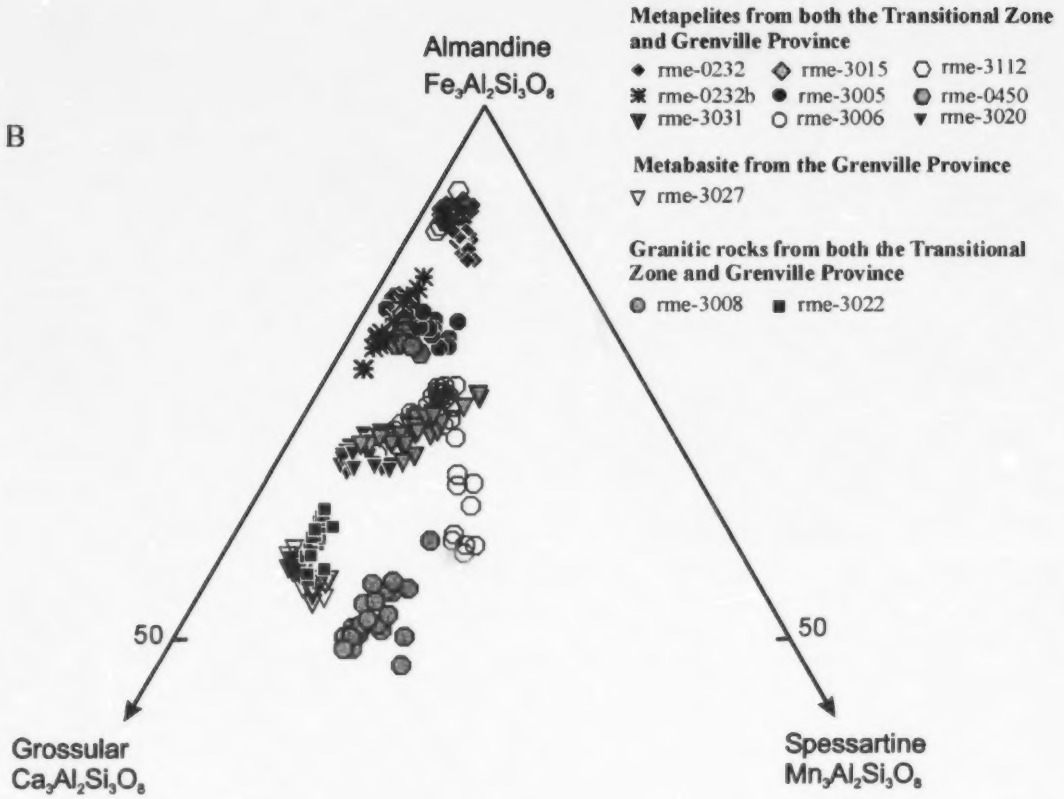


Figure 13. a) Garnet composition space applicable to the Timmins Creek area. b) Range in composition of garnets from Timmins Creek area samples in terms of mole % CaO-FeO-MnO projected from mole % MgO.

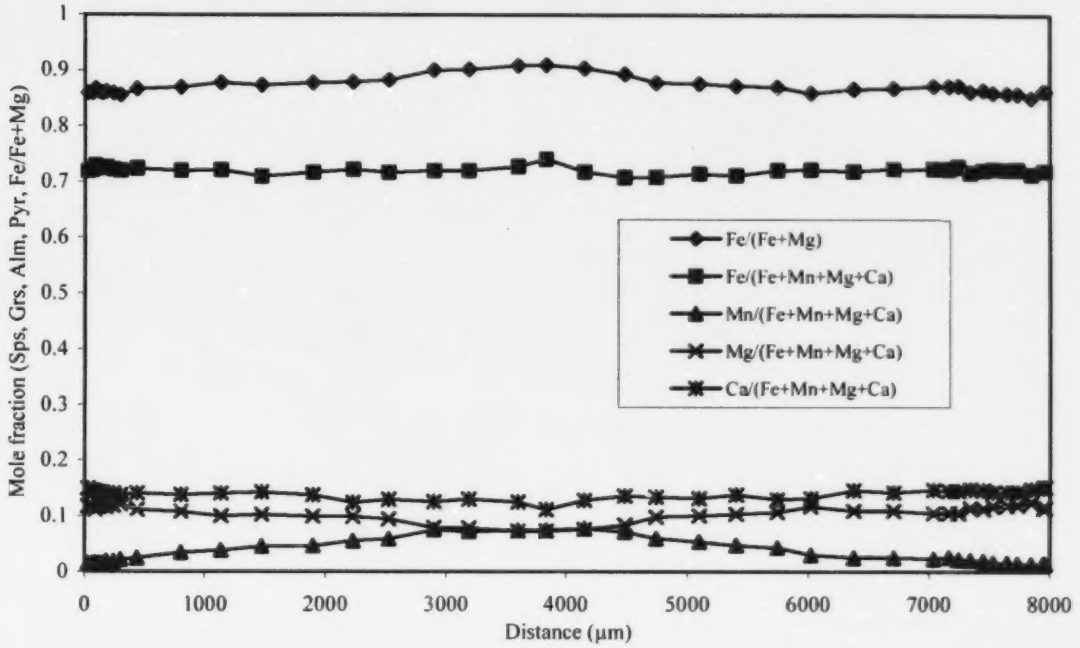


Figure 14. Compositional traverse across a garnet from a metapelitic schist (rme-3005) from the Transitional Zone in the Timmins Creek area.

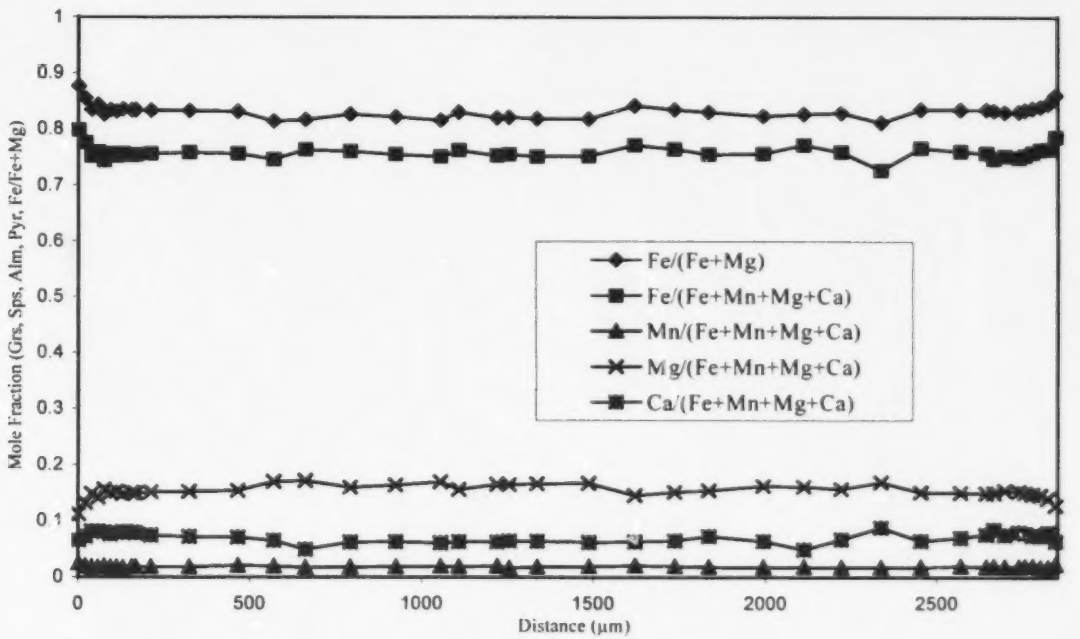


Figure 15. Compositional traverse across a garnet from a metapelitic schist (rme-3112) from the Transitional Zone in the Timmins Creek area.

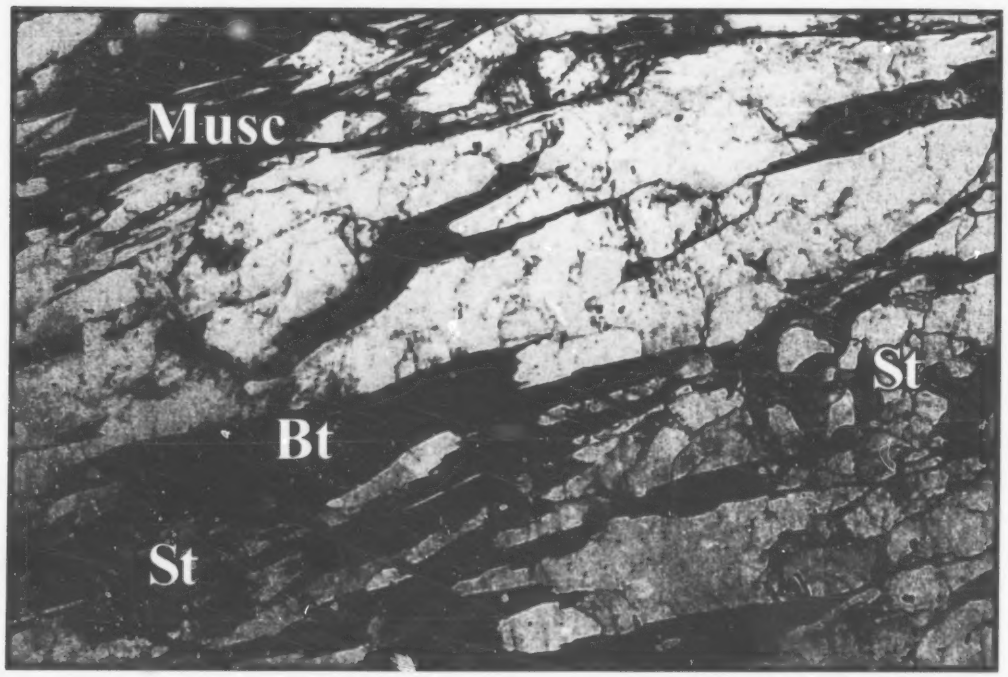


Photo 39. Thin section view of a kyanite-staurolite-garnet-biotite-muscovite schist. Staurolite (St) crystals have sharp boundaries with muscovite (Musc), biotite (Bt), plagioclase and quartz. Field of view is 4.2 mm wide. Sample 96rme-3112, Transitional Zone.

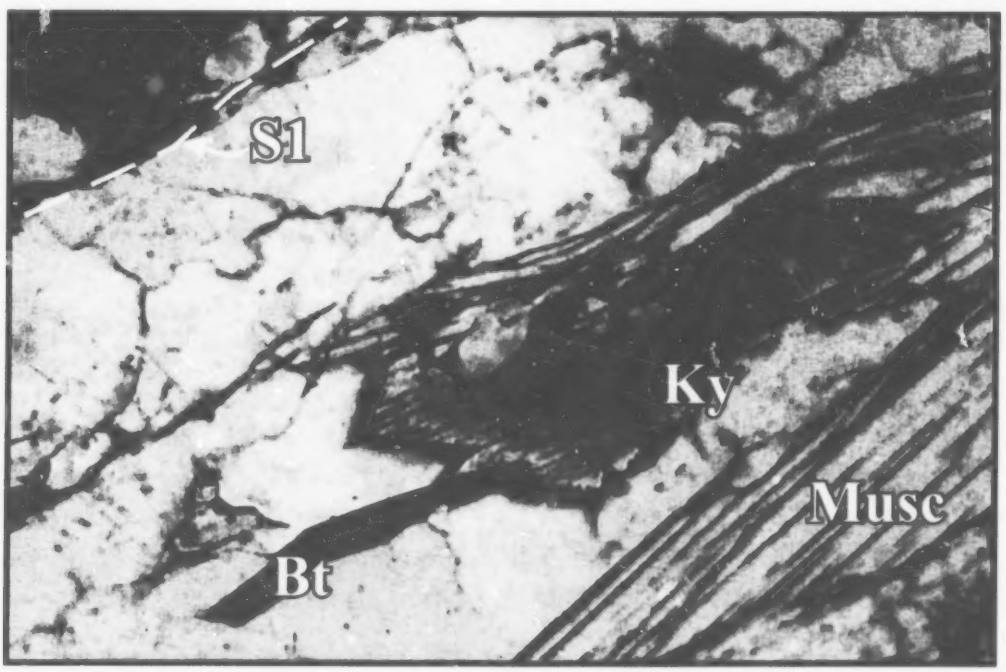


Photo 40. Kyanite (Ky) occurs as individual subidioblastic blades, oriented parallel to the S_1 foliation in a kyanite-staurolite-garnet-biotite (Bt)-muscovite (Musc) schist. Plane polarized light; field of view is 1.7 mm wide. Sample 96rme-3112, Transitional Zone.

MAFIC ROCKS

Mafic rocks within the Transitional Zone are represented by metamorphosed metavolcanic rocks ("Stobie Formation"), sills and dikes of Nipissing metagabbro, and narrow garnet-amphibolite metadikes, which intruded metasedimentary units in this area (Figure 6).

The mafic metavolcanic rocks are composed mostly of amphibole (70 to 80%) and plagioclase (15 to 20%) with small amounts of biotite and quartz (Table 1c). Accessory minerals include ilmenite, titanite, rutile, zircon and secondary chlorite and epidote. The nematoblastic texture of these rocks shows a strong lineation defined by ferrotschermakitic hornblende (Figure 16, after Leake (1997)) that lies within the S_1 fabric (Photo 41). Narrow felsic veinlets, 2 to 4 mm in width, are parallel to the S_1 foliation and consist of carbonate, quartz and garnet. The equilibrium assemblage of this unit, viz. ferrotschermakitic hornblende-plagioclase (An_{15-20})-biotite-titanite-ilmenite-epidote, indicates that these rocks underwent lower amphibolite facies grade of metamorphism. The occurrence of ferrotschermakitic hornblende has been documented in the polymictic conglomeratic schist unit. Because the amphibole in sample rme-3005 is the same as those in the mafic rocks, it is possible that the clasts in this sample are volcanic in origin, and derived from rocks similar to sample rme-3004.

The Nipissing metagabbro in the Transitional Zone is composed of calcic-amphibole, biotite, plagioclase, quartz and epidote with secondary chlorite and accessory amounts of titanite and opaque minerals. These rocks exhibit lepidoblastic textures, with biotite best defining the S_1 foliation (Photo 42). Ferropargasitic hornblende-plagioclase (An_{18-22})-biotite-epidote forms an equilibrium assemblage. The amphibole grains are relatively homogeneous in composition from core to rim; brown pleochroic biotite forms fine- to medium-grained laths; weak sericitic alteration occurs in some plagioclase grains; epidote forms good idioblastic crystals, which show a pronounced mineral zonation from core to rim (Photo 43). Along late shear zones (Figure 6), retrograde mafic assemblages consist of magnesiohornblende-epidote-albite-quartz (samples rme-3147, rme-3147-1) (Figures 11, 16; Photo 44). Pleochroism in magnesiohornblende varies from green to blue-green and some of these amphiboles are actinolitic hornblende (Figure 16). Plagioclase in these sheared and altered rocks is albite (An_{0-5}) (Figure 11). Estimates of the pre-alteration metamorphic plagioclase composition were determined by scanning 5 by 8 µm (at 13 000 magnification) using an analytical SEM. The estimated composition is An_{45-50} (Figure 11).

The garnet-amphibolite metadike (Figure 6) is composed of Ca-amphibole, plagioclase, garnet, quartz and biotite. Epidote, titanite and opaque minerals occur accessory ones (Table 1c). Slight elongation of dark green hornblende and brown biotite define a lineation in the S_1 foliation plane. Syn- to posttectonic garnets occur as xenoblastic to subidioblastic grains, which are highly poikiloblastic and contain inclusions of quartz, plagioclase, opaque minerals, biotite and secondary chlorite (Photo 45). The garnet-hornblende-biotite-plagioclase assemblage is in equilibrium and corresponds to conditions of the middle amphibolite facies of metamorphism (Bucher and Frey 1994).

Binary plots of Ca-amphibole compositions from the Transitional Zone show a distinct (prograde) trend for the mafic rocks. This is illustrated in Figures 17 and 18. Decreasing trends in Al_2O_3, TiO_2, FeO, MnO, Na_2O, K_2O versus SiO_2 and increasing trends in MgO and CaO versus SiO_2 are interpreted to indicate an increase in metamorphic grade from lower amphibolite facies (samples rme-3004, rme-3005) to middle amphibolite facies (samples rme-3145, rme-3145-1, rme-0132) (Miyashiro 1961, 1973). The amphiboles in the prograde metamorphic assemblage (samples rme-3004, rme-3005, rme-3145, rme-3145-1) in the mafic rocks all plot along a clear trend in the compositional diagrams presented in Figures 17 and 18. All the amphibole compositions indicate conditions of low to middle amphibolite facies (Bucher and Frey 1994). This is consistent with the observations from the pelitic rocks. The retrograde assemblage in the mafic rocks lying along the shear zone north of the Grenville Front boundary fault (samples rme-3147, rme-3147-1) consist of green magnesiohornblende to actinolitic hornblende, together with albite, epidote and chlorite. These minerals formed at conditions transitional from greenschist to amphibolite facies (Bucher and Frey 1994) and likely developed after peak metamorphism.

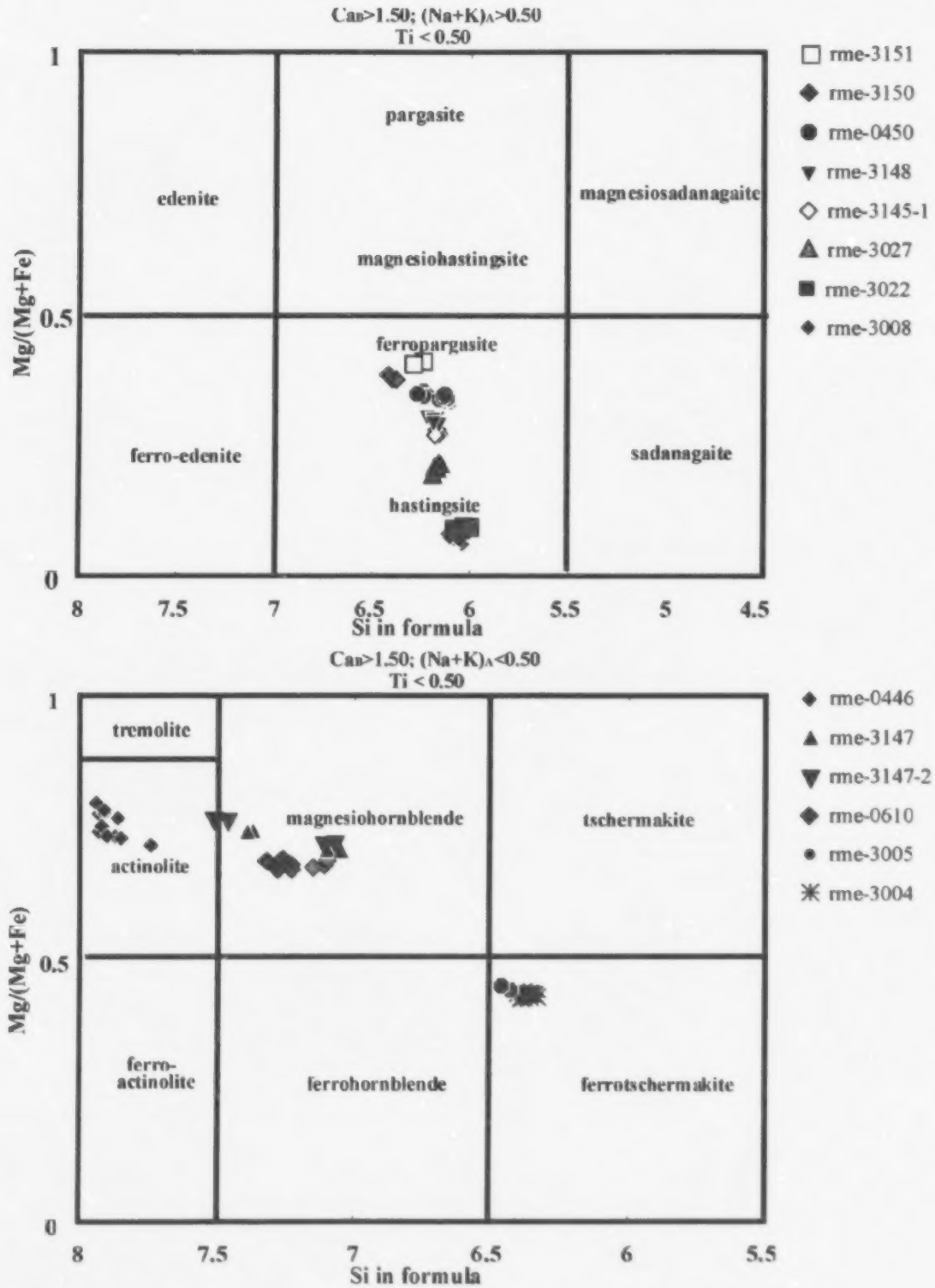


Figure 16. Amphibole compositions from metabasic, metapelitic and granitic rocks in the Timmins Creek area.

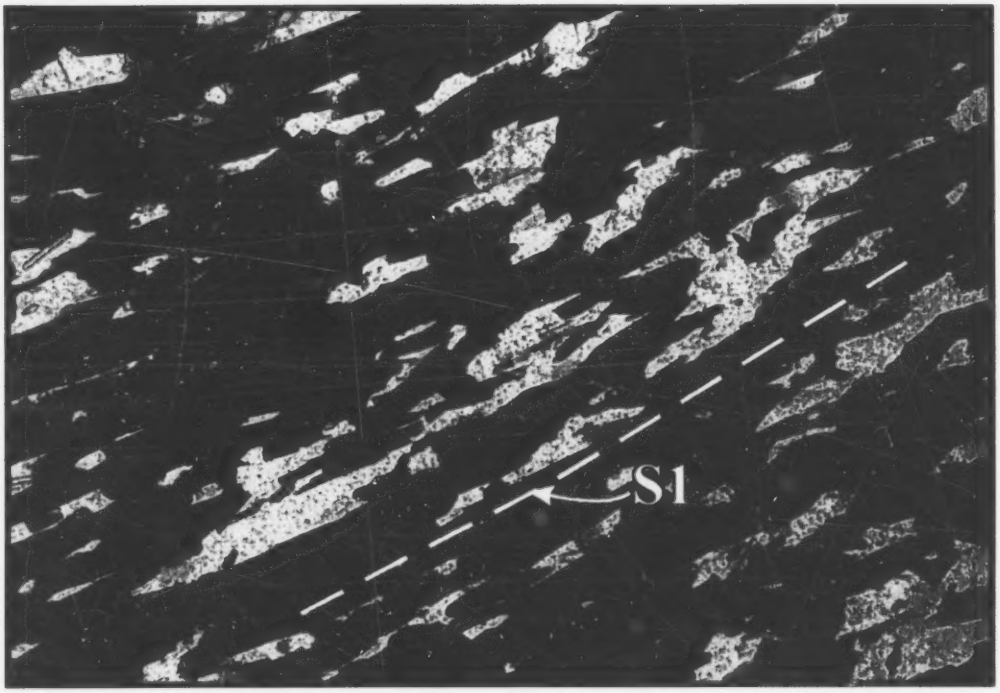


Photo 41. Nematoblastic texture within a metabasite shows a pronounced orientation in the plane of the S_1 fabric. Plane polarized light; field of view is 1.7 mm wide. Sample 96rme-3004, Transitional Zone.

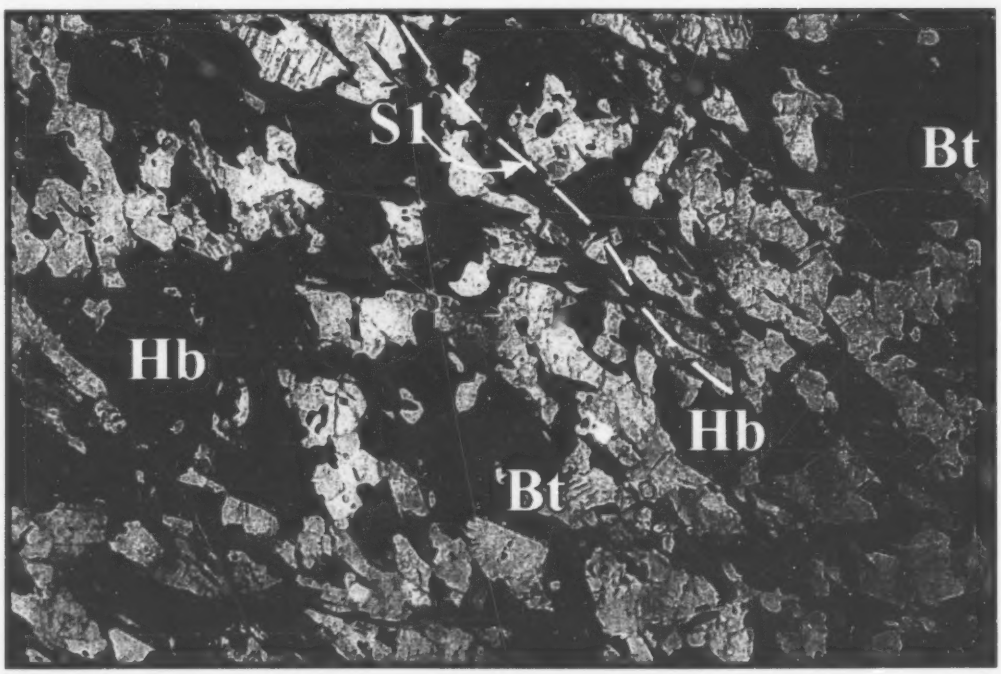


Photo 42. Lepidoblastic texture typical of mafic amphibolites (Hb) derived from Nipissing gabbro. Biotite (Bt) defines the S_1 foliation. Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-3145-2, Transitional Zone.

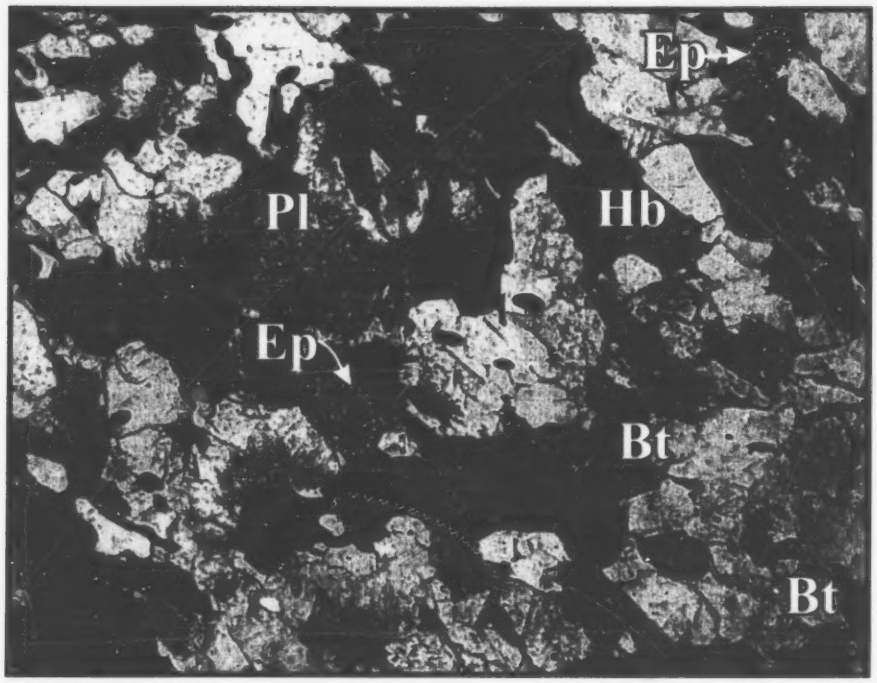


Photo 43. Thin section view of a mafic amphibolite derived from Nipissing gabbro. Amphibole (Hb) forms fine- to medium-grained crystals; weak sericite alteration occurs in some plagioclase (Pl) grains. Epidote (Ep) forms idioblastic crystals that show zonation from core to rim. Field of view is 1.7 mm wide. Sample 96rme-3145-1, Transitional Zone.

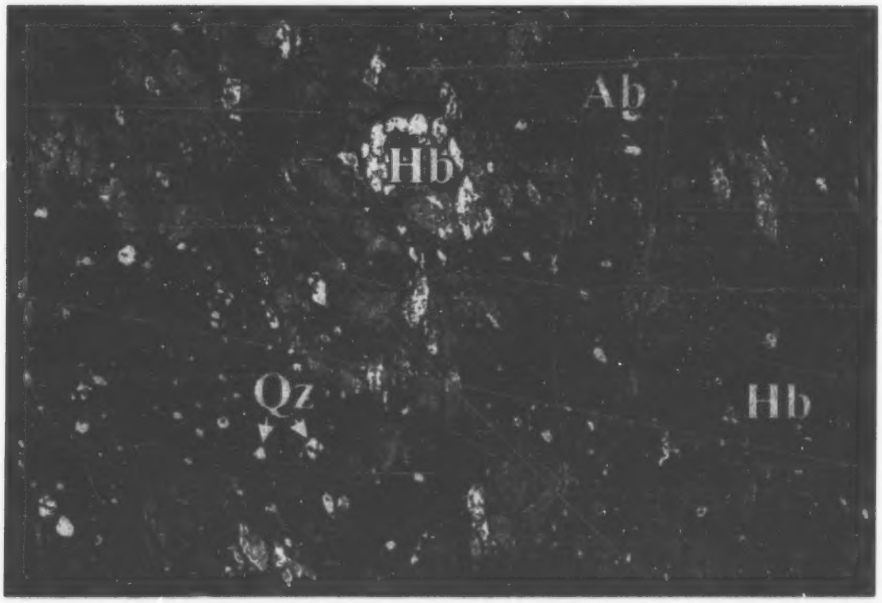


Photo 44. Retrograde epidote-amphibole(Hb)-quartz-plagioclase (Ab) assemblage developed in mafic amphibolite (Nipissing gabbro) along a shear zone that lies parallel to the Grenville Front boundary fault. The dark mineral is a fine-grained secondary chlorite-epidote-albite-quartz assemblage that replaces plagioclase. Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-3147-1, Transitional Zone.

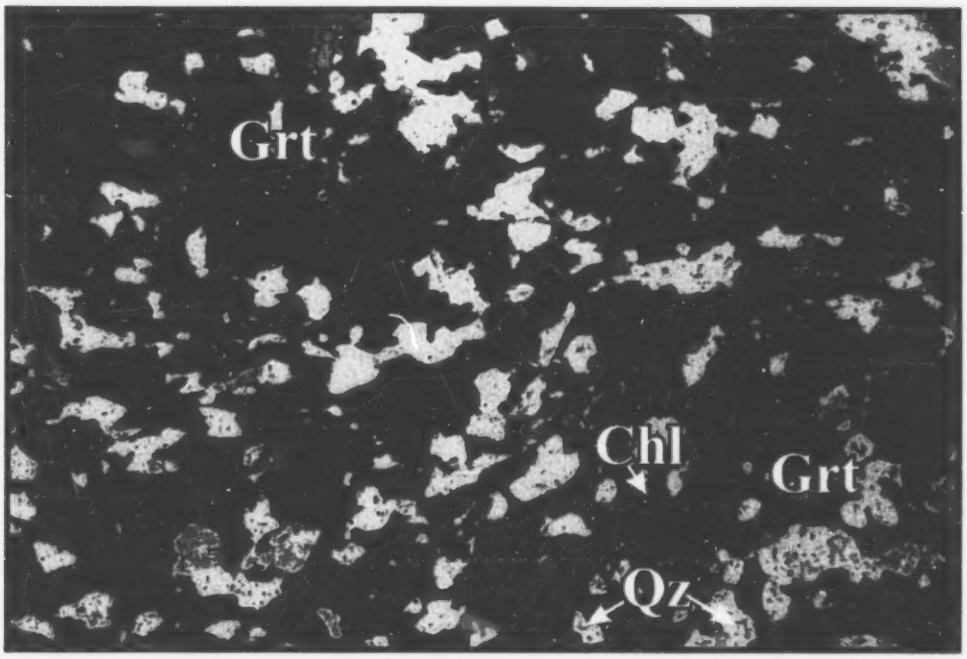


Photo 45. Xenoblastic to subidioblastic grains of garnet (Grt) within a mafic dike are highly poikiloblastic and contain inclusions of quartz (Qz), plagioclase, opaques, biotite and secondary chlorite (Chl). Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-0132, Transitional Zone.

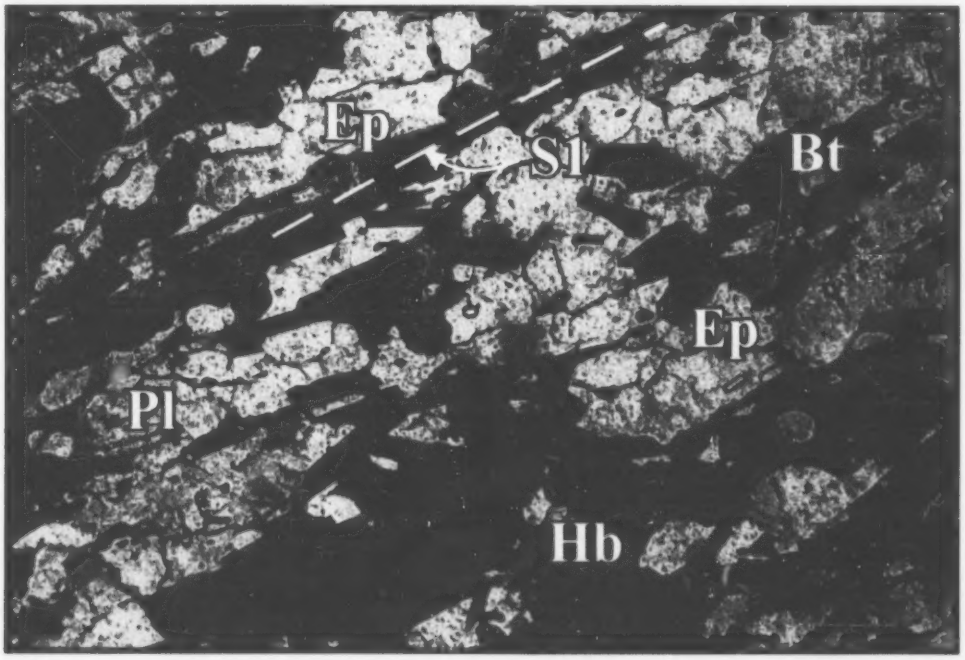


Photo 46. Thin section view of a felsic metavolcanic rock, showing lepidoblastic texture and distinct elongation of hornblende (Hb), plagioclase (Pl) and brown-green biotite (Bt) along the S_1 foliation. Epidote (Ep) forms zoned idioblastic crystals. Field of view is 1.7 mm wide. Sample 96rme-3042, Transitional Zone.

FELSIC ROCKS

Felsic rocks include felsic metavolcanic rocks and metamorphosed granitoids (Figure 6). The major mineral phases in both felsic rock types are plagioclase, potassium feldspar, quartz, biotite, Ca-amphibole, secondary chlorite and accessory amounts of titanite, rutile, epidote, apatite and opaque minerals. Garnet occurs only in the metamorphosed granites. Felsic metavolcanic rocks exhibit lepidoblastic textures and distinct alignment of subidioblastic hastingsitic hornblende (Figure 16), plagioclase (An_{20-22}) (Figure 10b) and brown pleochroic biotite along the S_1 foliation (Photo 46). The S_1 fabric is less pronounced in the granoblastic textures of the granitic units (samples rme-3144, rme-3008), where it is defined by brown-black laths of biotite (Photo 47). Sub- to idioblastic garnets in metagranites have poikiloblastic cores and

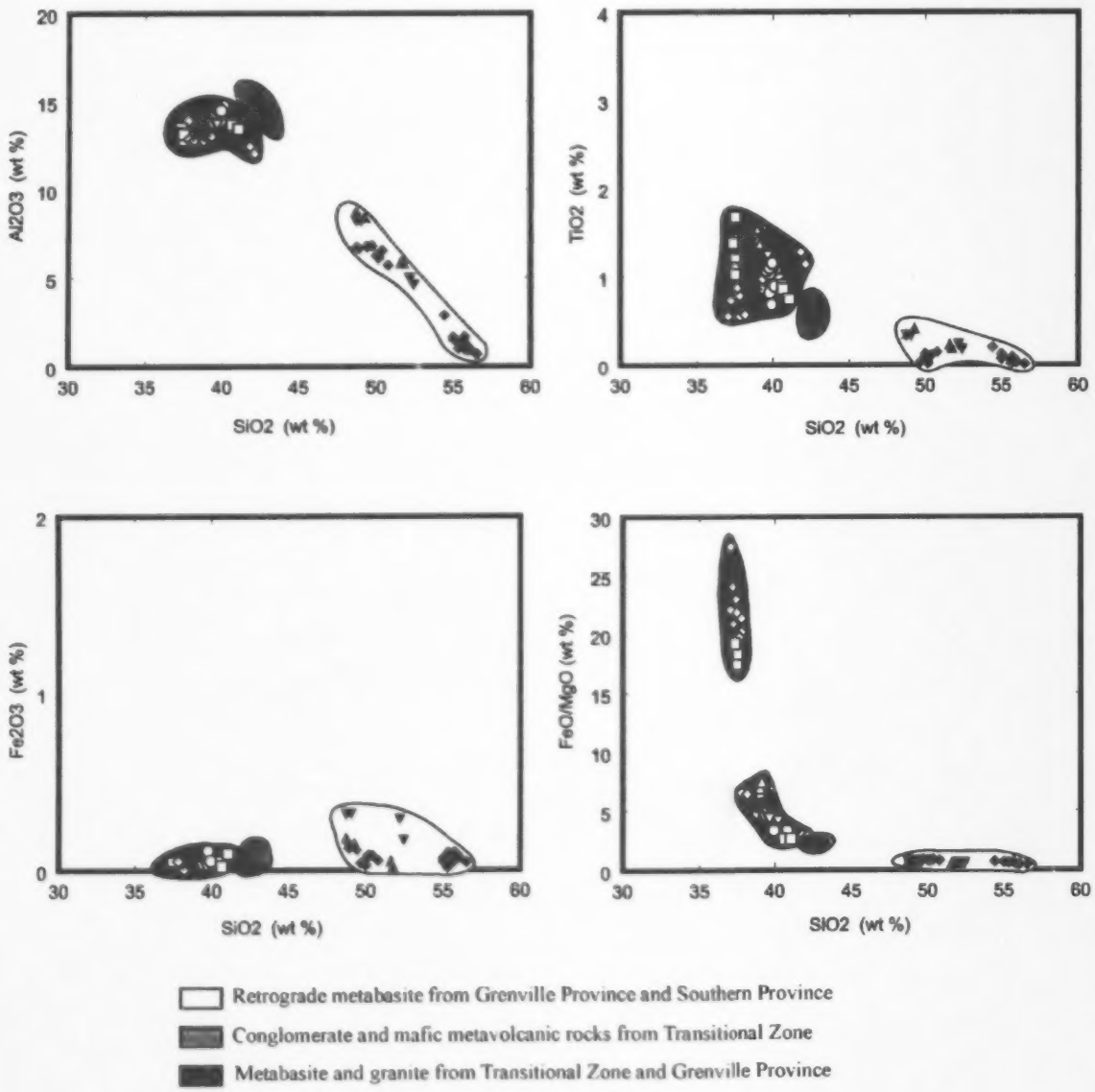

Al2O3 (wt %)
SiO2 (wt %)
TiO2 (wt %)
SiO2 (wt %)
Fe2O3 (wt %)
SiO2 (wt %)
FeO/MgO (wt %)
SiO2 (wt %)
Retrograde metabasite from Grenville Province and Southern Province
Conglomerate and mafic metavolcanic rocks from Transitional Zone
Metabasite and granite from Transitional Zone and Grenville Province

Figure 17. Binary plots showing the chemical variation in calcic amphiboles from rocks of the Timmins Creek area.

inclusion-free rims (Photo 48). They are indicative of syn- to posttectonic garnet growth. The equilibrium assemblage for the granitic rocks is hastingsitic hornblende (Figure 16) -plagioclase (An_{12-22}) (Figure 10b) -biotite (Figure 12)-muscovite-garnet (Figure 13) -potassium feldspar-quartz.

Coloured mica in the granitic rocks is magnesium rich and plots in the phlogopite field (Figure 12). Analyses of amphiboles in the Transitional Zone for the felsic rocks have been plotted on the binary compositional diagrams (Figures 17, 18). These plots show that the Ca-amphiboles in these rocks lie in the same compositional domain as those from the mafic rocks (metavolcanic rocks and Nipissing metagabbro) in the Transitional Zone domain, suggesting that the felsic units experienced similar metamorphic conditions (i.e., amphibolite facies).

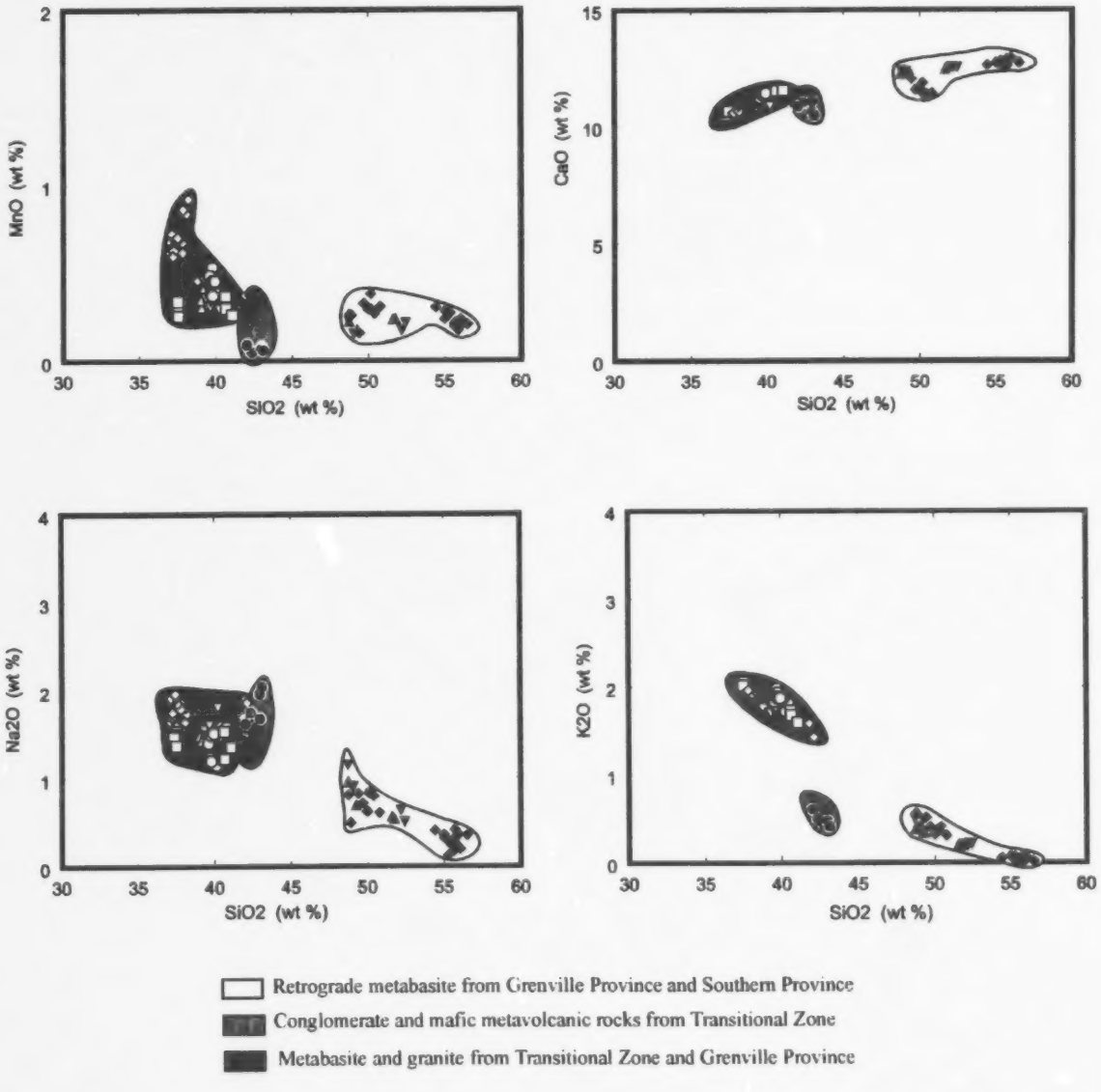

MnO (wt %)
SiO2 (wt %)
CaO (wt %)
SiO2 (wt %)
Na2O (wt %)
SiO2 (wt %)
K2O (wt %)
SiO2 (wt %)
Retrograde metabasite from Grenville Province and Southern Province
Conglomerate and mafic metavolcanic rocks from Transitional Zone
Metabasite and granite from Transitional Zone and Grenville Province

Figure 18. Binary plots showing the chemical variation in calcic amphiboles from rocks of the Timmins Creek area.

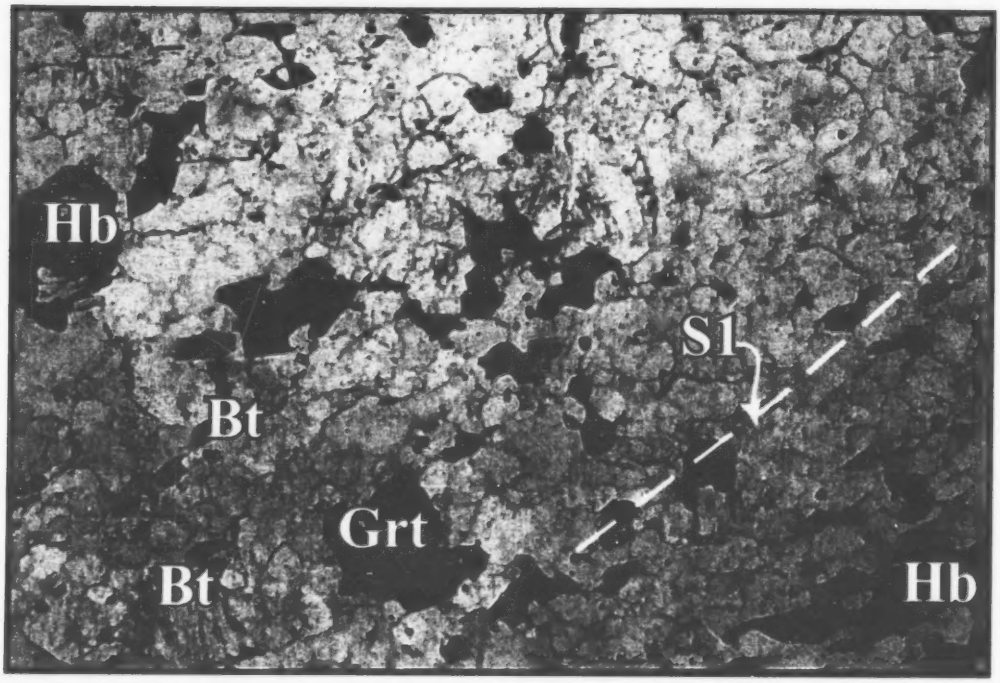


Photo 47. The S_1 fabric is typically less pronounced in the granoblastic-textured granitic rocks of the Transitional Zone. The fabric is defined by dark laths of biotite (Bt). Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-3008. Hb, hornblende; Grt, garnet.

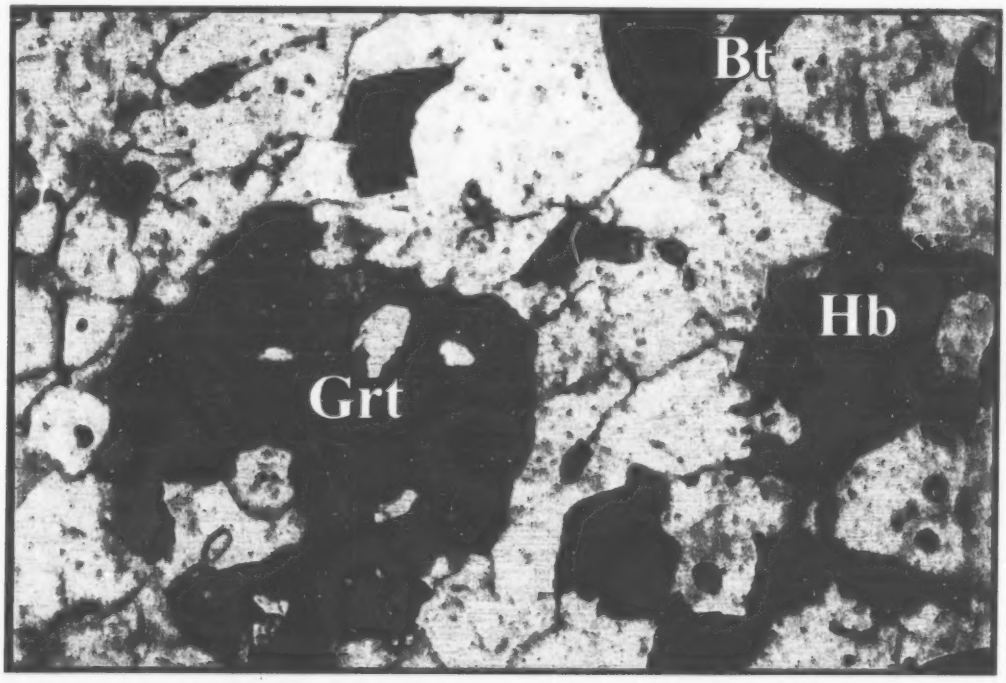


Photo 48. Sub- to idioblastic garnet (Grt) with poikiloblastic core and inclusion-free rim in a granitic rock from the Transitional Zone. Plane polarized light; field of view is 1.7 mm wide. Sample 96rme-3008. Hb, hornblende; Bt, biotite.

Grenville Province

Three main groups of rocks are recognized in this domain by analogy with the previously described Transitional Zone. These groups are 1) metapelites including staurolite-kyanite-garnet-muscovite gneiss, garnet-biotite and garnet-muscovite gneisses, 2) amphibolite gneisses, and 3) granitic gneisses (Figure 6). Macroscopic descriptions of pelitic rock units from the study area described previously show a transition from schists in the Transitional Zone domain to gneisses in the Grenville Province domain. The occurrence of syn-F_1 leucosomes and pegmatites in these rocks suggests that they have reached a stage of partial melting in their metamorphic history. As previously noted, post-F_2 granitic pegmatites also occur in this domain. The absence of both types of pegmatites in the Transitional Zone is significant.

PELITIC ROCKS

Three varieties of metapelitic gneisses were mapped in the Grenville Province domain (viz. staurolite-kyanite-garnet, garnet-biotite and garnet-muscovite gneisses) (Figure 6). All exhibit lepidoblastic textures in a coarse-grained matrix which hosts poikilitic garnet porphyroblasts. Biotite and muscovite define a folded S_1 fabric in these rocks (Photos 49 and 50). Mineral compositions of biotite in these assemblages are very similar to those from the Transitional Zone. The significant differences occur in 1) the modal proportions of some mineral phases (sample rme-0242), 2) grain size, and 3) the presence of granitic leucosome in the gneisses.

The staurolite-kyanite bearing gneisses (sample rme-0242) in this domain shows identical modal mineralogy to the kyanite-staurolite schist from the Transitional Zone (sample rme-3112) (Figure 6). In Figures 11a, 12 and 13, the chemical analyses of plagioclase, biotite and garnet, respectively, plot in the same population group as those from the Transitional Zone. This correlation in the mineral chemistry of the major phases suggests that these rocks have the same protolith and underwent similar metamorphic conditions. The whole rock geochemistry also establishes that the kyanite-staurolite-garnet-muscovite rocks on either side of the Grenville Front boundary fault have the same composition. There is a difference in the metamorphic grade for metapelites from the Transitional Zone and the Grenville Province domains. In the Grenville Province gneisses, kyanite is abundant, whereas staurolite occurs in trace amounts in kyanite-staurolite bearing assemblages. Sub- to idioblastic blades of kyanite are oriented parallel to the folded S_1 foliation (Photo 50) and are diagnostic of these pelitic gneisses. In the kyanite-bearing rocks, staurolite occurs as small, scarce, xenoblastic inclusions dispersed within the garnet porphyroblasts and kyanite blades (Photo 51), and as elongate and apparently very scarce crystals in the S_1 foliation plane (Photo 52). The clear dominance of modal kyanite over staurolite in these rocks compared to the opposite relationship for the same assemblage in the Transitional Zone suggests that the continuous reaction St + Bt = Ky + Grt has neared completion in favour of the products in the higher grade domain. Within the Grenville Province, the equilibrium assemblage St-Ky-Grt-Bt-Musc-Pl (An_{20})-Qz indicates that this rock corresponds to middle to upper amphibolite facies (Bucher and Frey 1994).

MAFIC ROCKS

Speculation on the protolith for different types of amphibolite gneisses within the Grenville Province is discussed in another section (*see* "Geochemistry"). The majority of these gneisses within the study area are correlated with the Nipissing diabase. A typical mineral composition consists of hornblende, plagioclase (An_{30}), biotite, garnet and epidote. Petrographic studies reveal similarities in texture, mineral chemistry and composition with the mafic rocks in the Transitional Zone. The differences between these

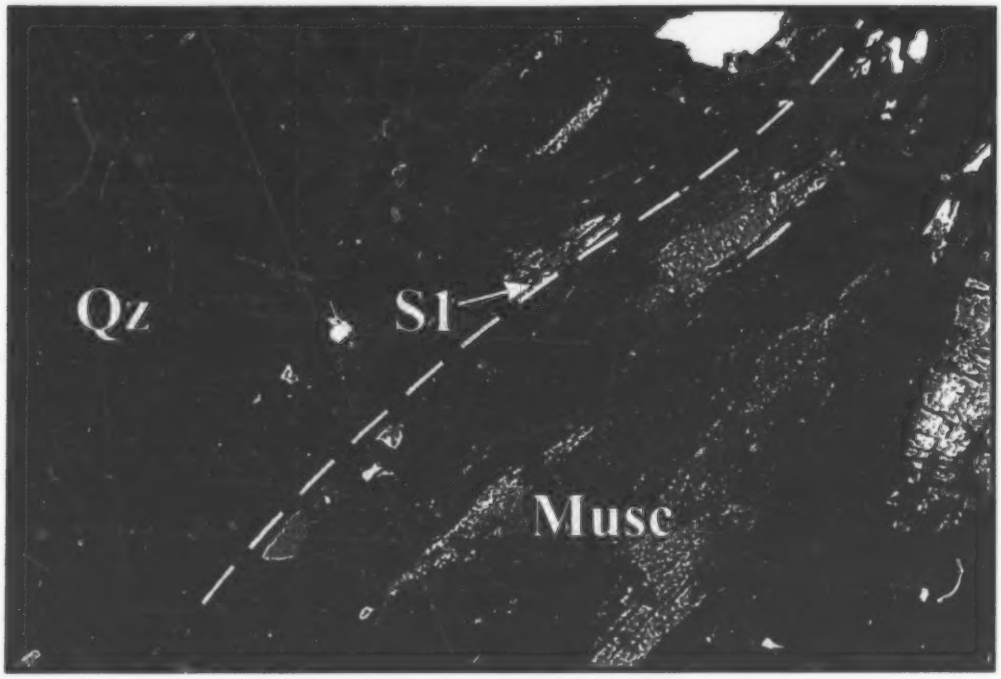


Photo 49. Mica grains, including muscovite (Musc), are oriented parallel to the S_1 fabric in a coarse-grained metapelitic gneiss of the Grenville Province. Crossed nicols; field of view is 4.2 mm wide. Sample 96rme-3028. Qz, quartz.

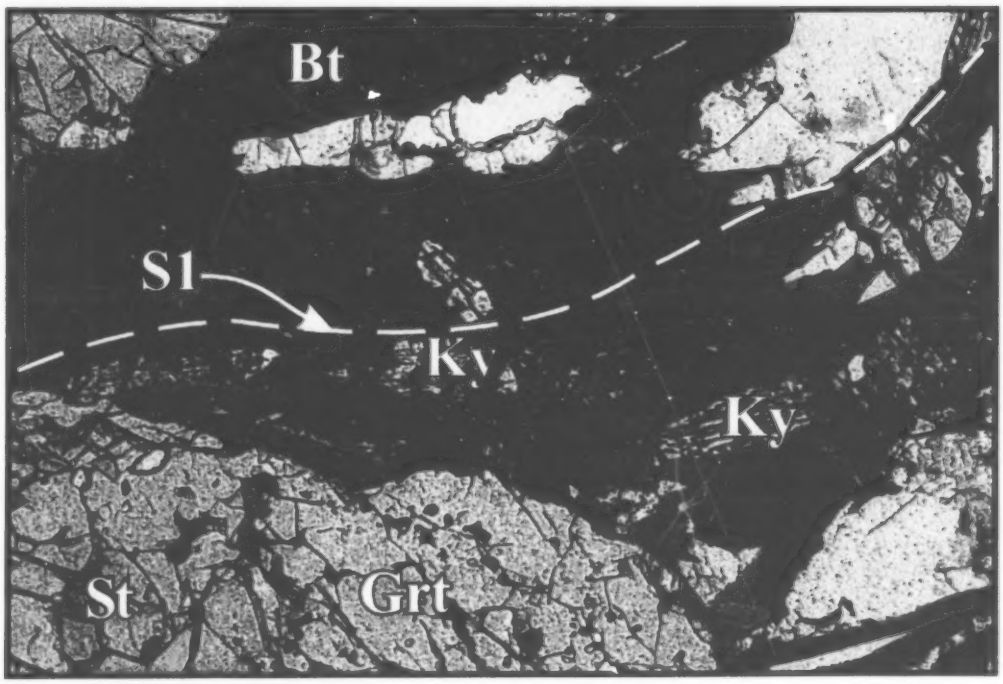


Photo 50. Thin section view of a kyanite-staurolite(St)-garnet(Grt)-muscovite-biotite(Bt) gneiss from the Grenville Province. Sub- to idioblastic blades of kyanite (Ky) are oriented parallel to the S_1 foliation. Field of view is 4.2 mm wide. Sample 96rme-0242.

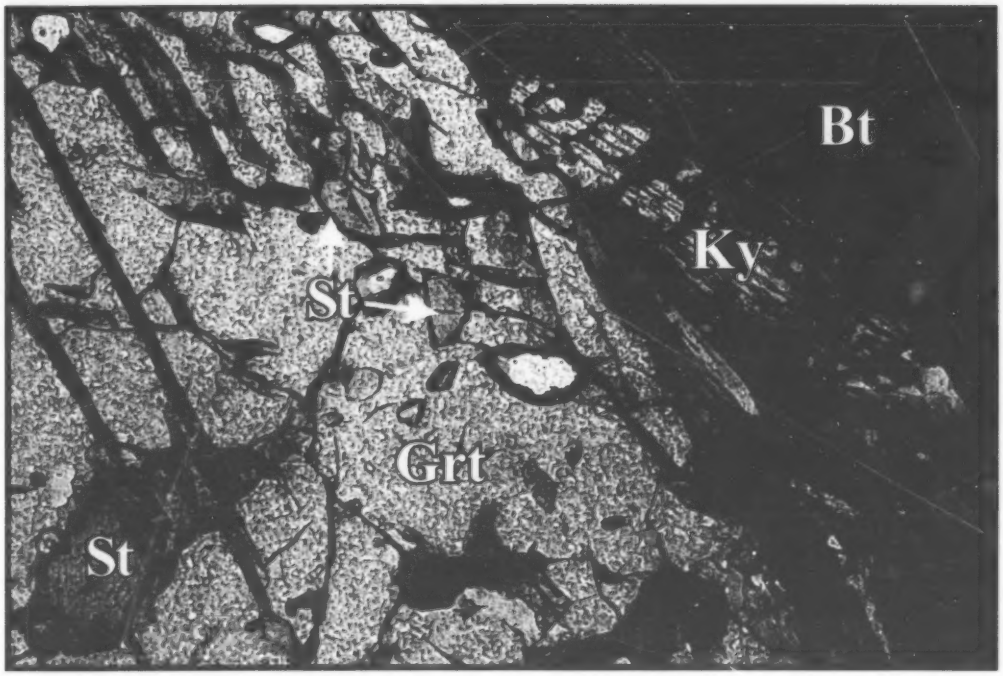


Photo 51. Close-up view of a kyanite(Ky)-staurolite-garnet-muscovite-biotite(Bt) gneiss from the Grenville Province. Staurolite (St) occurs as small, scarce, xenoblastic inclusions dispersed within a garnet (Grt) porphyroblast. Plane polarized light, field of view is 1.7 mm wide. Sample 96rme-0242.

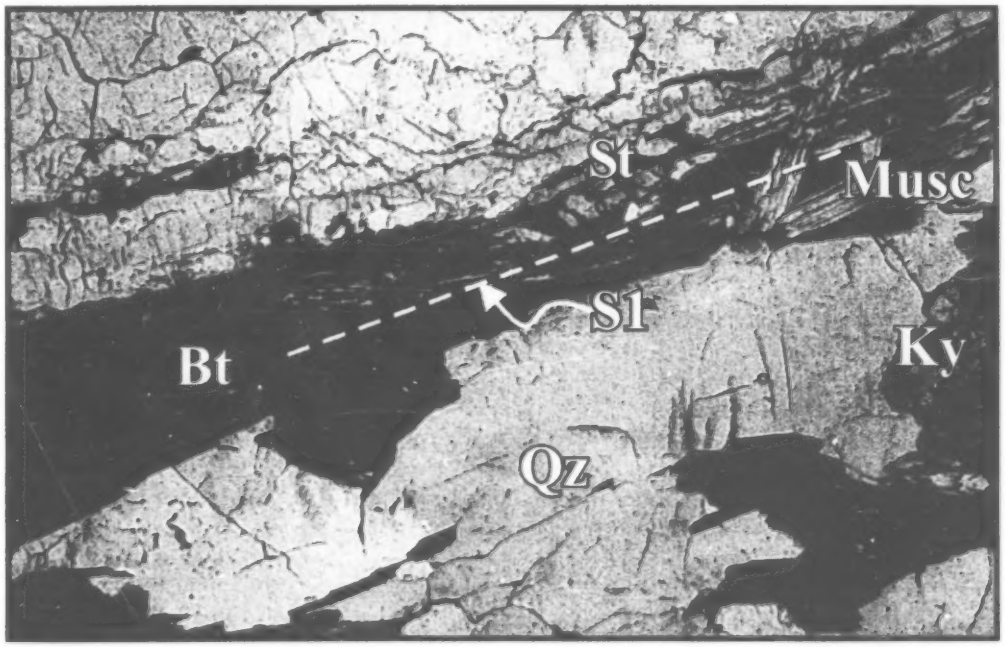


Photo 52. Small individual grains of staurolite (St) occur as elongated crystal along the S_1 foliation in a kyanite(Ky)-staurolite-garnet-muscovite(Musc)-biotite(Bt) gneiss from the Grenville Province. Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-0242.

rocks in the Grenville Province are mainly in 1) grain size, and 2) presence of felsic lenses and ribbons, which define the discontinuously banded, gneissic textures on the macroscopic scale. In the classification diagram for the calcic amphiboles in Figure 16, their compositions are ferropargasitic hornblende rather than hastingsitic hornblende as in the Transitional Zone (Figure 16). These differences in amphibole chemistry are also shown in Figures 17 and 18 (samples rme-3148, rme-3149, rme-3150). Plagioclase compositions in the mafic rocks are slightly higher in anorthite components in the Grenville Province (Figure 11b). This is probably due to a reaction that produces magnesium-rich ferropargasitic hornblende and calcic plagioclase from hastingsitic hornblende and epidote or clinozoisite. An epidote-group mineral is stable at this metamorphic grade (upper amphibolite) until this continuous reaction goes to completion (Bucher and Frey 1994).

FELSIC ROCKS

In general, granitic gneisses of the Grenville Province consist of plagioclase (An_{15-18}), hornblende, and biotite and exhibit a similar amphibolite facies paragenesses to those from the Transitional Zone. The main differences between felsic rocks in the Grenville Province and the Transitional Zone are 1) grain size and 2) gneissic textures within the Grenville Province. These features also characterize the differences in the metapelites and mafic rocks between these two domains. The similarities in the granitic rocks from the Transitional Zone and Grenville Province are shown in the mineral chemistry, and textures at the thin section level (Photo 53). This is demonstrated in Figure 12 where the composition of the biotites for the two domains plots in the same group. The anorthite component in plagioclase is almost identical with those from the Transitional Zone (Figure 10b). Compositions of amphiboles from the both zones practically overlap each other in the Figure 16 (Leake 1997) and correspond to hastingsitic hornblende. On the binary composition diagrams, these amphiboles plot as one distinctive population group (Figures 17, 18).

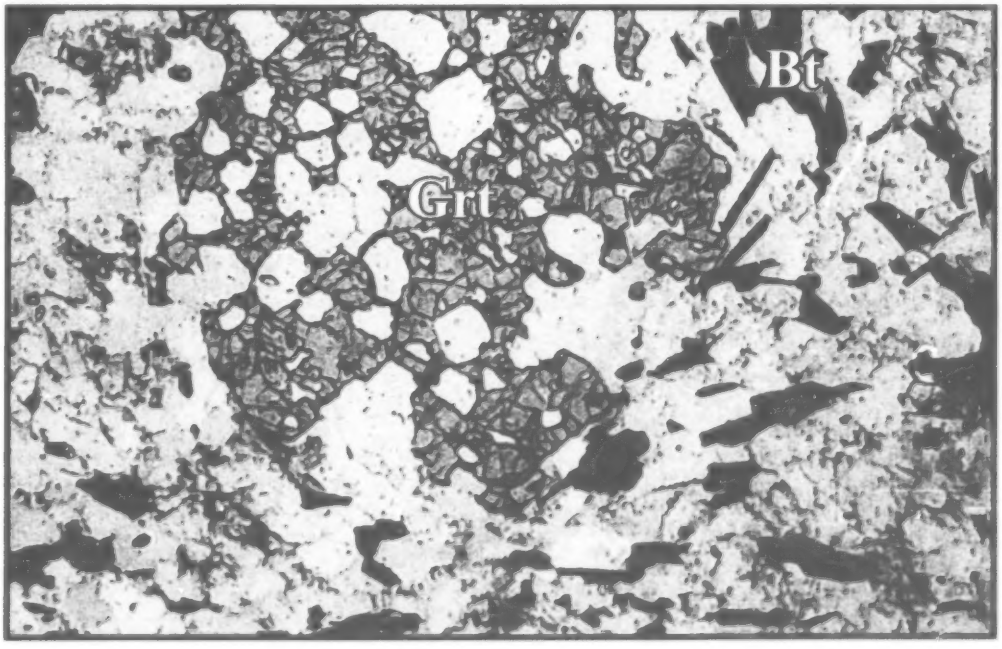


Photo 53. A garnet (Grt) porphyroblast with a highly poikiloblastic texture is present in a granoblastic granitic gneiss from the Grenville Province. Plane polarized light; field of view is 4.2 mm wide. Sample 96rme-3022. Bt, biotite.

The only major mineralogical change observed within the metagranite occurs along the Grenville Front boundary fault, which marks the boundary between the Transitional Zone and the Grenville Province. Here, large amounts of retrograde minerals, notably chlorite and hematite, are present (Photo 29). These minerals suggest greenschist facies metamorphic conditions along this fault, consistent with the observation of greenschist facies conditions from shear zones within mafic rocks in the Transitional Zone, as described in a previous section.

Summary

In conclusion, the petrography and mineralogy of the different rock units within the Transitional Zone indicate that they were subjected to low to middle amphibolite-facies grade metamorphism. Transition from the low to middle amphibolite facies is recorded from the north to south in the Transitional Zone, particularly in the mafic rocks. This observation is based on 1) coarsening grain size of these rocks to the south, 2) prograde change in the distinctive equilibrium mineral assemblages to the south, and 3) the amphibole chemistry in the mafic rocks. The presence of the staurolite-kyanite-muscovite-biotite assemblage in the metapelites from the southern part of the Transitional Zone indicates that the metamorphic grade is middle amphibolite facies, consistent with the mafic rock assemblages in the same area. For kyanite-bearing rocks, Bucher and Frey (1994) estimate that staurolite-biotite in metapelites is first stable at ~610°C via the reaction Grt + Chl = St + Bt. Using this temperature and aluminosilicate phase reactions (Kerrick 1990), a minimum load pressure of 5.5 kbar (~20 km) is required to form this assemblage.

The fact that the staurolite breaks down and forms garnet-kyanite in sample rme-0242, containing the Ky-Grt-Bt-Musc-Pl (An_{25-30}) assemblage, marks the beginning of the upper amphibolite facies. This boundary also coincides with the production of the first melt in rocks of suitable composition at water-saturated conditions (Bucher and Frey 1994). In this respect, the Grenville Front boundary fault does not separate vastly different rock units or rocks of vastly different metamorphic grade, but simply marks the metamorphic boundary between middle and upper amphibolite grade facies.

THERMOBAROMETRY

In thermobarometry, the most important factor for the determination of temperatures and pressures is complete equilibration of the relevant mineral assemblage. In "Petrology", the major equilibrium assemblages were described within the metamorphic rocks of the three domains of the thesis area: Southern, Transitional and Grenville.

For *P–T* calculations, measurements of the coexisting mineral compositions are required. This was done on a JEOL JSM-6400 scanning electron microscope (SEM) using an energy dispersive spectroscopy (EDS) detector. The data were processed using a ZAF-4 correction program. Several criteria were met for acquiring reliable chemical analyses: 1) careful calibration, 2) using one or more standards, 3) checking the analytical totals (weight percent), and 4) mineral stoichiometry.

There are several methods to estimate the pressure and temperature of metamorphic reactions. The main principle for all methods is that, at given *P* and *T*, mineral phases are associated with unique values of molar Gibbs free energy (*G*). Rocks represent heterogeneous thermodynamic systems (Gibbs 1961), where minerals, aqueous fluids and gases are the thermodynamic phases. In the study area, these phases are staurolite, kyanite, garnet, biotite, muscovite, Ca-amphibole, plagioclase, quartz, ilmenite, rutile and water.

Methods

Two approaches have been used in this study to quantitatively estimate the conditions of metamorphism in the Transitional Zone and Grenville Province of the study area. The most rewarding is the use of low variance mineral assemblages that permit the calculation of numerous equilibria whose area of intersection is an estimate of the conditions at which the assemblage formed. TWEEQU (Berman 1991) and INVEQ (Gordon 1996) are software programs used to explore this approach. The second approach is focused on exchange reactions where individually calculated mineral thermometers are used to estimate temperature.

The computer software program TWEEQU – version 1.02 (Thermobarometry With Estimation of EQUilibrium state) was developed by Berman (1991). This program contains a thermodynamic database for a wide variety of end-member minerals and mineral composition solution models for garnet, biotite, plagioclase, white mica and Ca-amphibole. The free energy (G) of these minerals at P and T is calculated from these thermodynamic data using equations of state given by the laws of chemical thermodynamics. According to these laws, the chemical components making up a total rock composition are distributed into a group of homogeneous phases (minerals and fluids), which constitute the assemblage with the lowest free energy for the system for that given pressure and temperature. This assemblage is most stable.

TWEEQU uses the requirement that when products and reactants of a chemical reaction ($\Delta G = G_{products} - G_{reactants}$) are both stable, then $\Delta G_{reaction} = 0$. These conditions are referred to as the equilibrium conditions of the reaction and in P–T space can be expressed by a single curve. Along this curve, all minerals are simultaneously stable and any intersection with related univariant equilibria gives estimates of the temperature and pressure at which the mineral assemblage formed. For any perfectly behaved system (all minerals equilibrate at the same P,T; reliable mineral composition; standard state and mixing properties), the calculated phase diagram should have all equilibria intersecting at a unique point (Berman 1991). The degree to which all reaction curves converge to the single point is ideally directly proportional to the state of equilibrium among the phases. Minor mineral phases, viz. rutile, ilmenite, which cause more scatter of the reaction curves in the P–T space have been omitted in this study order to more accurately approach the single convergence point.

Chemical homogeneity of coexisting minerals in the rocks is an important factor for obtaining a best estimate of the equilibration of mineral pairs (assemblages). For this reason, a series of garnet-biotite and plagioclase-amphibole pairs have been analyzed to provide data on the homogeneity of these phases. Among many combinations, the data pairs have been divided into two groups. The first group represents analyses of rims of matrix biotite in contact with the rim of garnet. The second group represents core analyses of biotite and garnets grains. This group has been chosen for the P–T calculations to avoid late re-equilibration (retrograde) between phases. Both garnet and biotite are relatively uniform in composition. The same two groups involve core and rim analyses of the plagioclase-amphibole pair.

Adjacent mineral pairs were analyzed, because they had the best opportunity to equilibrate. To decrease analytical error, 2 to 3 analyses were done for each mineral phase. Average mineral compositions were used for the final thermodynamic calculations. Core compositions give the highest P, T determinations indicating they probably recorded the peak of metamorphism, whereas rim compositions yield the lowest values due to re-equilibration during retrograde metamorphism. In this study, core-generated data are normally reported.

INVEQ (INVerse of chemical EQUilibrium) is a software program developed by Gordon (1996) and is available on the World Wide Web. The program allows the inverse of the classical "chemical equilibrium problem" to be performed. It allows determination of P–T, at which a mineral assemblage

formed, given the composition of mineral phases. The TWEEQU database is used in INVEQ as a source for calculating the thermodynamic activities of components in the relevant minerals.

The main advantage of the INVEQ is the fact that, at equilibrium, the partial molar free energies of all end-members should lie on a single plane. In this approach, the *P* and *T* of equilibrium are found by finding the best-fit plane to the partial molar free energies of all end members rather than a set of independent equilibria as calculated by TWEEQU. In this section, the results of calculations using INVEQ are compared with those using TWEEQU program for the relevant mineral assemblages.

Geothermometers

Two types of thermometers are used in this study: garnet-biotite and amphibole-plagioclase. The thermometers are based on the interchange of two similar atoms between different sites in one mineral (amphibole) or between two minerals (garnet-biotite, amphibole-plagioclase). Because the exchange atoms are elements of similar charge and ionic radius, the volume changes involved are very small and the entropy changes relatively large (Bucher and Frey 1994). Therefore, exchange reactions are largely independent of pressure and have good value as thermometers.

The garnet-biotite thermometer is based on the Mg-Fe exchange between annite-phlogopite and almandine-pyrope (Hodges and Spear 1982). The amphibole-plagioclase thermometer is based on the coupled substitution Ca + Al = Na(K) + Si, where the substitutions in amphibole for alkalis in the A site and Si/Al_{IV} in the T_1 site (Holland and Blundy 1994). The actual calculations were done using a Microsoft Excel spreadsheet developed by F. Ford (Geoscience Laboratories, personal communication, 1997, 1998).

Results

Two samples from the study area, one from each of the Transitional Zone and the Grenville Province, best illustrate estimated pressure and temperature conditions of metamorphism on either side of the Grenville Front boundary fault (Figure 19). These samples are from metapelites; they both contain the phases staurolite, kyanite, garnet, biotite, muscovite, plagioclase and quartz. These are the lowest variance assemblages (variance = 1) recognized in these two metamorphic zones. As a result, they provide the maximum number of linearly independent reactions (3/4; anhydrous/hydrous system) to estimate the temperature and pressure of formation.

Figure 20a demonstrates the TWEEQU plot for sample rme-3112 from the Transitional Zone (Figure 6). Six anhydrous phases (Ky, Grt, Bt, Musc, Pl, Qz) from this sample produce three linearly independent reactions indicating that the sample last equilibrated at $P = 7.35$ kbar and $T = 660°C$ (using the INTERSX program, TWEEQU). Figure 20b shows the TWEEQU plot for the same sample when staurolite and H_2O are included in the calculation. The total number of linearly independent reactions in this analysis is four. To obtain similar *P–T* data (i.e., 660°C, 7.35 kbar) to that calculated for the anhydrous assemblage (including the good convergence for all reactions (as shown in Figure 20b)), the activity of water in the fluid (αH_2O_{FL}) has been varied from 1.0 to 0.87. The latter value gives the best fit to the anhydrous calculations and, so, indicates that the fluid that has equilibrated with this assemblage was not pure water (H_2O). All reactions in this calculation are presented in Table 2. Using the same data for the anhydrous phases for this sample, the program INVEQ was applied. It gives similar results: $P = 7.3$ kbar, $T = 660°C$ with the error estimations of ±1 kbar and ±50°C respectively (Figure 21a).

Figure 22a shows the TWEEQU plot for the sample rme-0242 from the Grenville Province (Figure 6). Using the same anhydrous phases as for sample rme-3112, similar reactions were calculated. The

convergence point of the three independent reactions gives $P = 8.14$ kbar and $T = 685°C$. With staurolite and H_2O fluid included, four linearly independent reactions were calculated for the same assemblage (Figure 22b). They converge at $P = 8.2 \pm 1$ kbar and $T = 685 \pm 50°C$, which are identical conditions to the anhydrous assemblage when the activity of H_2O in the fluid is $\alpha H_2O_{FL} = 0.83$. In Table 2, a list of all the linearly independent reactions are presented. The calculated fluid composition is clearly very similar to that recorded for rocks in the Transitional Zone. The results using the INVEQ program for the anhydrous assemblage give $P = 8.1 \pm 1$ kbar and $T = 684 \pm 50°C$ (Figure 21b).

On the P–T diagram (Figure 23) both of the samples described above plot to the right of the melting curve for muscovite + quartz when $\alpha H_2O_{FL} = 1$. When the activity of H_2O in the fluid is changed to 0.83 to 0.87, the melting curve will shift to higher temperatures. The new position of the melting curve has not been determined, but field and petrological constraints indicate it must lie between the Transitional Zone and Grenville Province domain samples as illustrated in Figure 23. This might explain why partial melting (migmatites) is only observed in the Grenville Province samples.

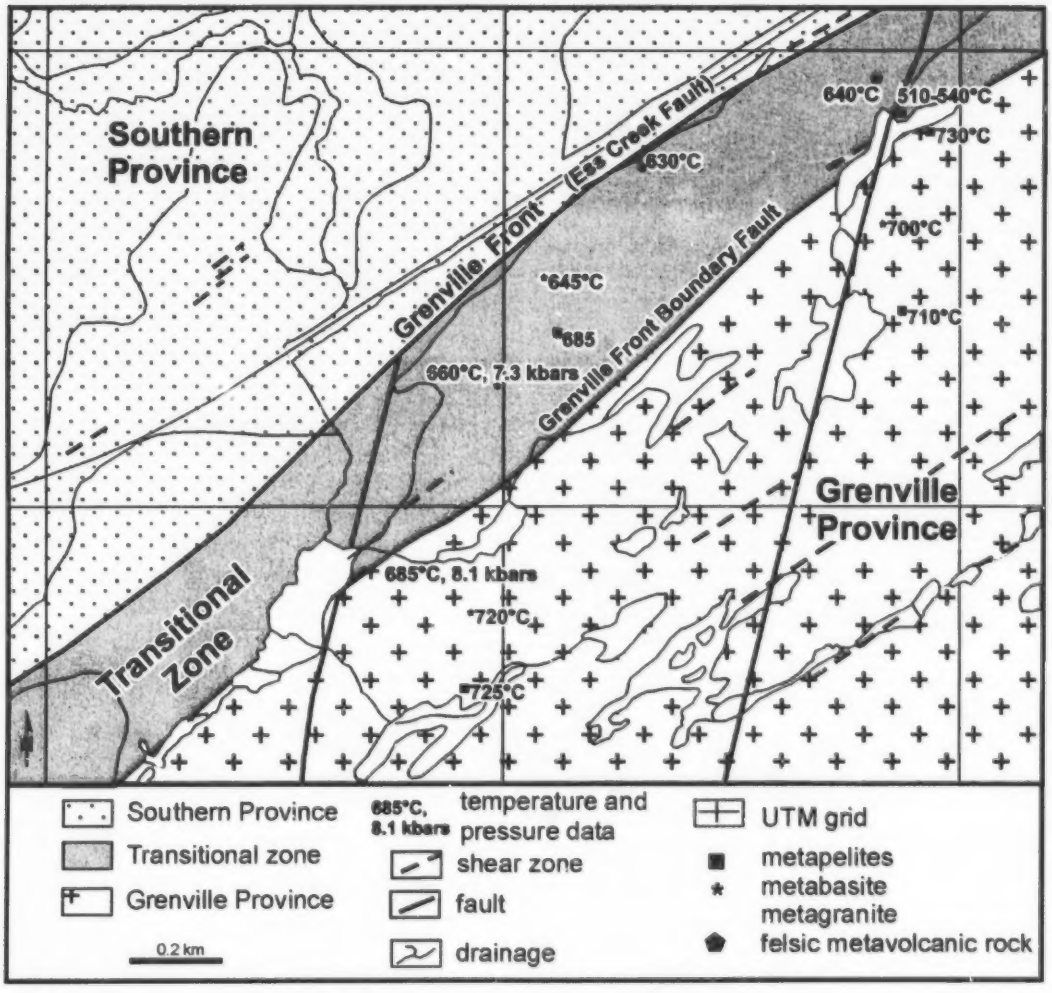


Figure 19. Metamorphic facies map with P–T data obtained from the rocks in the Timmins Creek area.

Temperature conditions for other metapelites from the Transitional Zone and Grenville Province were estimated using garnet-biotite thermometry (Table 3). Assuming that pressure in the Transitional Zone is near 7.3 kbar (as obtained using TWEEQU and INVEQ for sample rme-3112), temperatures average 640°C (samples rme-3005, rme-3006). In the Grenville Province, the same approach for P = 8.1 kbar yields T = 715°C. The 20 to 30°C difference between these estimates and those generated by TWEEQU and INVEQ are within the ±50°C error (Table 3) inherent in such calculations. Nevertheless, field and petrological data previously presented clearly indicate that the Grenville Province assemblages crystallized at higher temperatures.

For mafic units throughout the map area, temperature estimations are based upon the amphibole-plagioclase thermometer calculated by Holland and Blundy (1994) (Table 3). These temperature estimates are determined with the assumption that P = 7.3 kbar for the Transitional Zone (as calculated by TWEEQU and INVEQ, sample rme-3112) and P = 8.1 kbar for Grenville Province (using TWEEQU and INVEQ, sample rme-0242). From north to south, temperatures increase from 630 to 725°C (Figure 19). These data are consistent with other thermobarometry and the geological and petrological databases. Locally, low temperatures were obtained from one sample (T = 509 to 542°C, sample rme-3147) (Figure 19); this likely reflects the effects of retrograde metamorphism along shear zones present in this area.

Temperature estimates for felsic rocks within both the Transitional Zone and the Grenville Province are presented in Table 3. The garnet-biotite thermometer (Hodges and Spear 1982) was applied to samples rme-3008 and rme-3022, where T = 685°C and T = 720°C, respectively. Using the hornblende-plagioclase thermometer (Holland and Blundy 1994), sample rme-0124 gives T = 640°C.

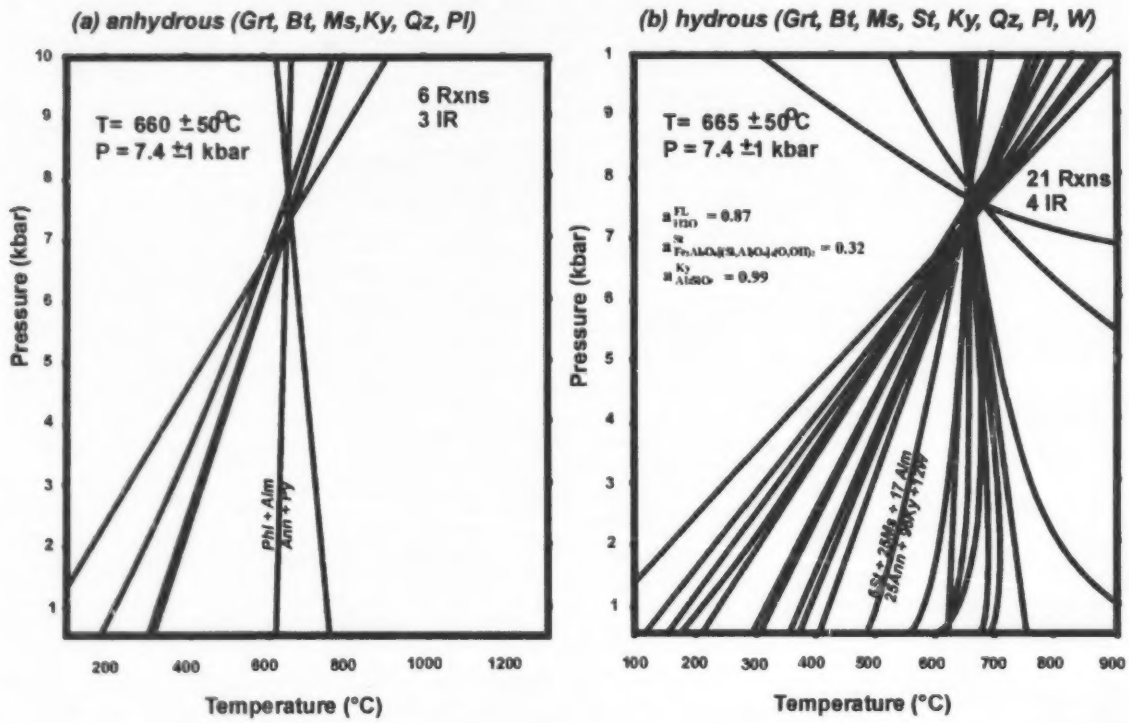


Figure 20. The equilibria generated by TWEEQU (Berman 1991) using anhydrous and hydrous facies from a metapelite (sample rme-3112) within the Transitional Zone in the Timmins Creek area. Reactions for equilibria shown in the plots are listed in Table 2.

In conclusion, thermobarometric results in the thesis area (Figure 19) show a progressive increase in temperature from north to south beginning at the Grenville Front (Ess Creek fault). These data are consistent with petrographic results that show increasing grade from north to south based on 1) grain size increase, 2) textural changes, 3) appearance of metamorphic indicator minerals (e.g., staurolite, kyanite) and 4) appearance of leucosome material indicating conditions of partial melting (migmatite formation).

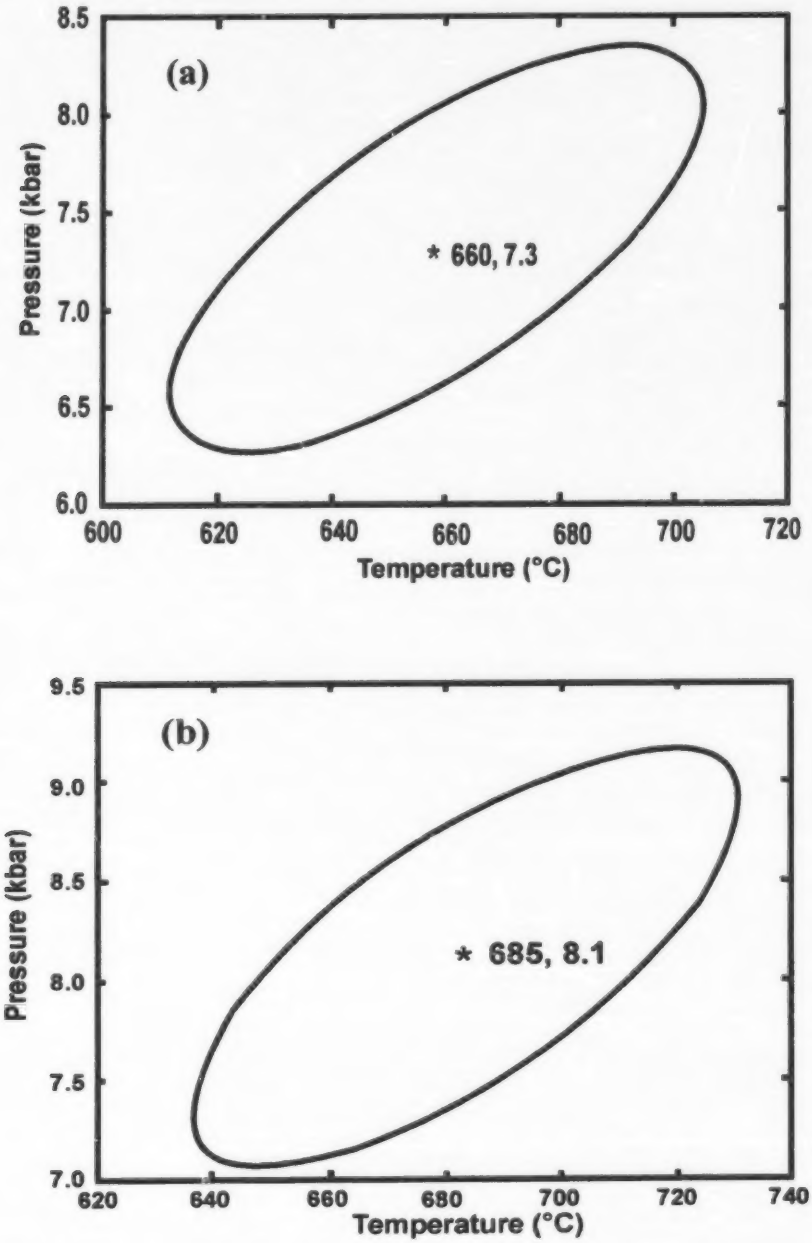


Figure 21. The *P–T* results generated by INVEQ (Gordon 1997) (using TWEEQU 1.03 database (Berman 1991)) from metapelitic rocks of the Transitional Zone (sample rme-3112) and the Grenville Province (sample rme-0242) in the Timmins Creek area.

The boundary of first leucosome appearance coincides with the Grenville Front boundary fault across which slight changes in pressure and temperature are indicated (Figure 19, Table 3). This is also consistent with the petrographic data where the Grenville Front boundary fault is described as a boundary of gradual transition between middle to upper amphibolite facies and not as an abrupt and substantial metamorphic boundary.

Although there are no direct *P–T* estimates on metamorphic conditions in the Southern Province in the study area, the first appearance of biotite suggests temperature ~350°C (Carmichael 1978). Studies elsewhere in the Southern Province (Fox 1971; Card 1978) show that andalusite is stable in pelites, indicating that Penokean regional metamorphism is a low to intermediate pressure type. Using Kerrick's (1990) estimate of phase relations in the Al_2SiO_5 system, for $T = 350°C$, load pressures (in the Southern Province) cannot be more than 3 kbar. These *P–T* data correspond to lower to middle greenschist facies conditions and is significantly different compared to middle and upper amphibolite facies for the Transitional Zone and the Grenville Province, respectively. These results indicate that a substantial metamorphic boundary lies parallel to the Ess Creek fault. This is the major tectonic boundary between the Southern and Grenville provinces in the study area, which the author now recognizes to be the location of the Grenville Front in Street Township. In Street Township, the Grenville Front has brought 1.0 billion-year-old, medium- to high-grade (625 to 725°C) rocks from the middle lower crust (7.3 to 8.1 kbar or ~25 km) into abrupt contact with an approximately 1.9 billion-year-old metamorphic terrain that has not exceeded low temperature (~350°C) and middle to upper crustal (3.5 kbar or ~12 km) depths of burial subsequent to the Penokean orogeny.

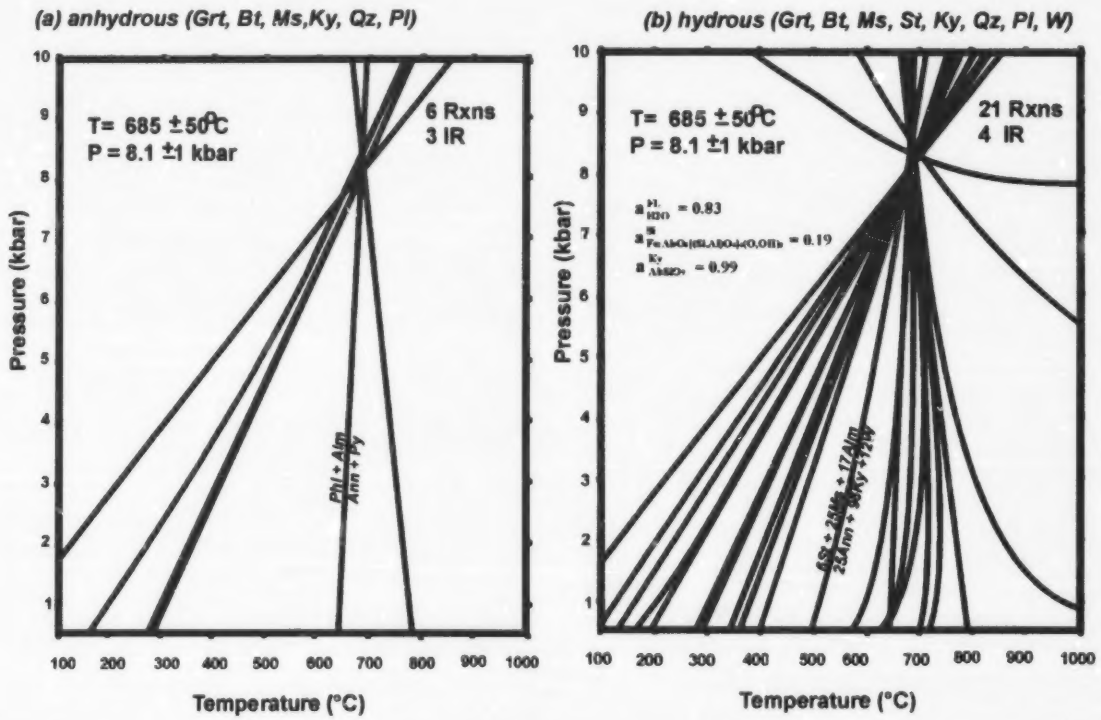


Figure 22. The equilibria generated by TWEEQU (Berman 1991) using anhydrous and hydrous facies from a metapelite (sample rme-0242) from the Grenville Province in the Timmins Creek area. Reactions for equilibria shown in the plots are listed in Table 2.

Table 2. A list of all equilibria generated by the TWEEQU program (Berman 1991) using anhydrous and hydrous phases from a) sample 96-rme-3112, and b) sample 96-rme-0242.

a) Sample 96-rme-3112.

Anhydrous	1	aQz + 2 Ky + Gr = 3 An
	2	Alm + Ms = aQz + 2 Ky + Ann
	3	Phl + Alm = Ann + Py
	4	Ms + Gr + Alm = Ann + 3 An
	5	Py + Ms = 2 Ky + Phl + aQz
	6	Py + Ms + Gr = 3 An + Phl
Hydrous	1	Alm + Phl = Py + Ann
	2	Gr + 2 Ky + aQz = 3 An
	3	Ms + Py = aQz + Phl + 2 Ky
	4	8 Ann + 46 Ky + 8 Py + 12 W = 6 St + 25 aQz + 8 Phl
	5	Ms + Alm = Ann + 2 Ky + aQz
	6	8 Alm + 46 Ky + 12 W = 6 St + 25 aQz
	7	Py + Ms + Gr = 3 An + Phl
	8	8 Py + 96 Ky + 25 Gr + 8 Ann + 12 W = 75 An + 8 Phl + 6 St
	9	6 St + 48 aQz + 8 Phl + 23 Gr = 8 Ann + 69 An + 8 Py + 12 W
	10	6 St + 17 Py + 25 Ms = 8 Ann + 96 Ky + 17 Phl + 12 W
	11	6 St + 17 aQz + 8 Ms = 8 Ann + 62 Ky + 12 W
	12	8 Ann + 23 Ms + 31 Py + 12 W = 6 St + 48 aQz + 31 Phl
	13	Ms + Gr + Alm = Ann + 3 An
	14	96 Ky + 25 Gr + 8 Alm + 12 W = 75 An + 6 St
	15	6 St + 48 aQz + 23 Gr = 8 Alm + 69 An + 12 W
	16	6 St + 25 Ms + 17 Alm = 25 Ann + 96 Ky + 12 W
	17	6 St + 25 Py + 25 Ms = 8 Alm + 96 Ky + 25 Phl + 12 W
	18	31 Alm + 23 Ms + 12 W = 6 St + 48 aQz + 23 Ann
	19	8 Alm + 23 Ms + 23 Py + 12 W = 6 St + 48 aQz + 23 Phl
	20	8 Ann + 17 Gr + 96 Ky + 12 W = 6 St + 8 Ms + 51 An
	21	6 St + 48 aQz + 8 Ms + 31 Gr = 8 Ann + 93 An + 12 W

b) Sample 96-rme-0242.

Anhydrous	1	aQz + 2 Ky + Gr = 3 An
	2	Alm + Ms = aQz + 2 Ky + Ann
	3	Phl + Alm = Ann + Py
	4	Ms + Gr + Alm = Ann + 3 An
	5	Py + Ms = 2 Ky + Phl + aQz
	6	Py + Ms + Gr = 3 An + Phl
Hydrous	1	Gr + 2 Ky + aQz = 3 An
	2	Alm + Ms = aQz + 2 Ky + Ann
	3	Phl + Alm = Ann + Py
	4	8 Alm + 46 Ky + 12 W = 6 St + 25 aQz
	5	Alm + Gr + Ms = 3 An + Ann
	6	96 Ky + 25 Gr + 8 Alm + 12 W = 75 An + 6 St
	7	6 St + 48 aQz + 23 Gr = 8 Alm + 69 An + 12 W
	8	Py + Ms = 2 Ky + Phl + aQz
	9	6 St + 25 Ms + 17 Alm = 25 Ann + 96 Ky + 12 W
	10	6 St + 17 aQz + 8 Ms = 8 Ann + 62 Ky + 12 W
	11	31 Alm + 23 Ms + 12 W = 6 St + 48 aQz + 23 Ann
	12	8 Ann + 46 Ky + 8 Py + 12 W = 6 St + 25 aQz + 8 Phl
	13	Py + Ms + Gr = 3 An + Phl
	14	96 Ky + 17 Gr + 8 Ann + 12 W = 51 An + 8 Ms + 6 St
	15	6 St + 48 aQz + 8 Ms + 31 Gr = 8 Ann + 93 An + 12 W
	16	8 Py + 96 Ky + 25 Gr + 8 Ann + 12 W = 75 An + 8 Phl + 6 St
	17	6 St + 48 aQz + 8 Phl + 23 Gr = 8 Ann + 69 An + 8 Py + 12 W
	18	6 St + 17 Py + 25 Ms = 8 Ann + 96 Ky + 17 Phl + 12 W
	19	6 St + 25 Py + 25 Ms = 8 Alm + 96 Ky + 25 Phl + 12 W
	20	8 Ann + 23 Ms + 31 Py + 12 W = 6 St + 48 aQz + 31 Phl
	21	8 Alm + 23 Ms + 23 Py + 12 W = 6 St + 48 aQz + 23 Phl

Note: The symbols used for the mineral names are those used in the TWEEQU program.

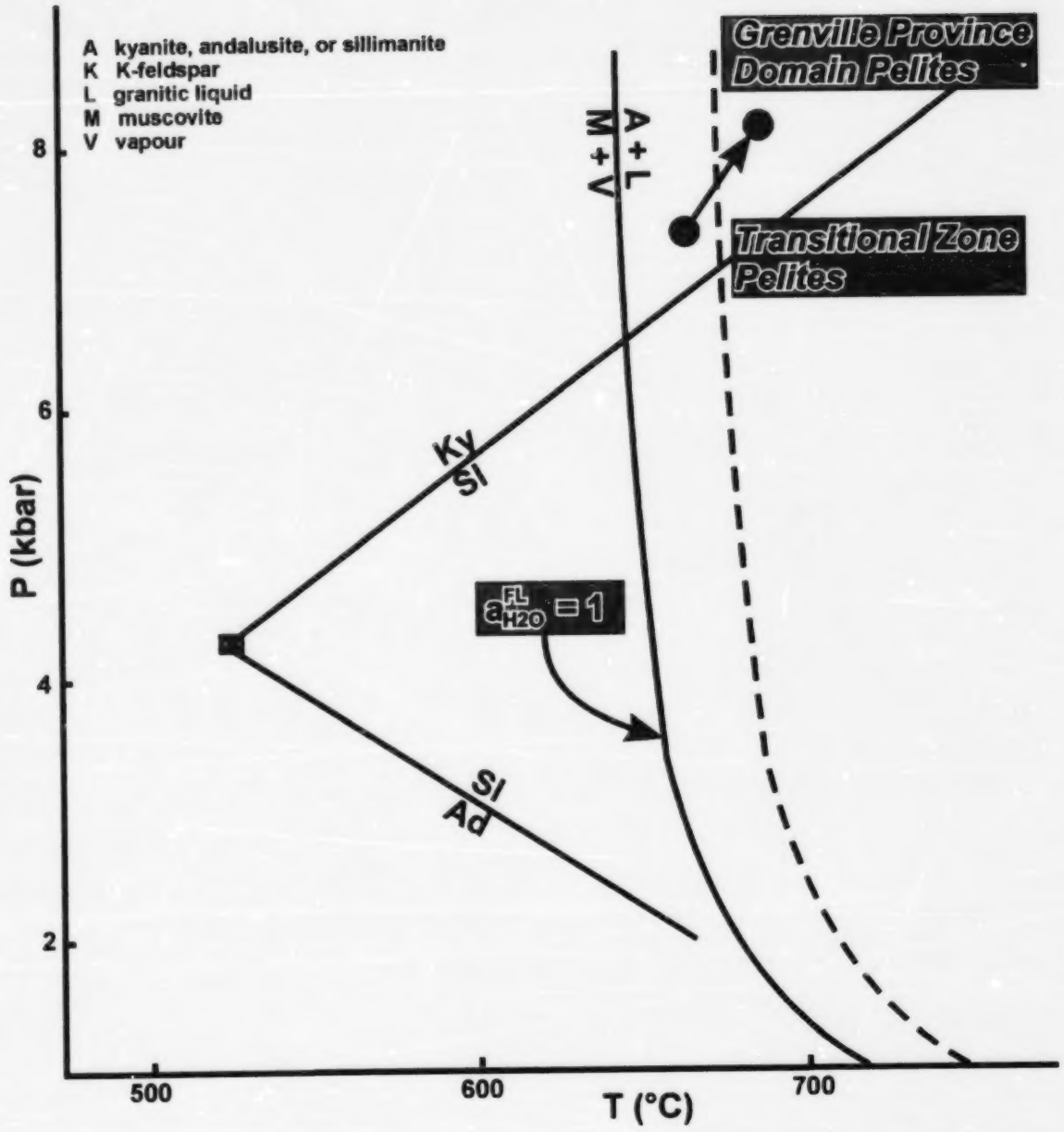


Figure 23. Plot showing the location of Timmins Creek samples in *P–T* space, as well as the change in *P–T* for metapelites from the Transitional Zone and the Grenville Province in the Timmins Creek area. Dashed line is the "estimated" position of the melting curve for muscovite + quartz. The diagram is simplified *from* Carmichael (1978).

Table 3. Pressure–temperature (*P–T*) estimates for metapelites, metabasites and felsic meta-igneous rocks from the Timmins Creek area, Street Township.

No.	Location	Sample Number, Rock Type	Methods (with estimates in kbar, °C) TWEEQU	INVEQ	Grt-Bt Thermometer	Hb-Pl Thermometer
1	Southern Province	rme - 0610, metabasite				2.0, 688.9 4.0, 674.0 6.0, 659.2
2	Transitional Zone	rme - 3004, metabasite	9.7, 627.1			6.0, 619.7 8.3, 646.8
3		rme -3005, metapelite	6.7, 630.2		5.5, 636.8 8.0, 646.0	
4		rme - 0124, felsic metavolcanic				6.0, 696.8 8.3, 708.2
5		rme - 3006, metapelite	7.5, 655.4 6.8, 615.2		5.5, 637.0 8.0, 645.7	
6		rme - 3031, metapelite			6.0, 623.7 8.0, 625.9	
7		rme - 3008, granite			5.5, 679.8 8.0, 688.5	6.0, 724.3 8.3, 726.2
8		rme - 0232a, metapelite	7.6, 678.0	7.6, 678.0	5.5, 680.1 8.0, 690.3	
9		rme - 0232b, metapelite	7.8, 645.0			
10		rme - 3112, metapelite	7.4, 660.0 7.4, 665.0	7.3, 660.0		
11		rme -3147, metabasite				6.0, 508.9 8.3, 509.4
12		rme -3147-2, metabasite				6.0, 539.0 8.3, 542.4
13	Grenville Province	rme - 3020, metapelite			5.5, 710.6 8.0, 719.8	
14		rme - 0242a, metapelite	7.7, 690.0		6.0, 649.8 8.0, 657.7	
15		rme - 0242, metapelite	8.1, 685.0	8.1, 685.0		
16		rme - 0450, metabasite				6.0, 681.0 8.3, 695.6
17		rme - 3027, metabasite				6.0, 718.5 8.3, 726.5
18		rme - 3022, granite	6.8, 713.0		5.5, 718.5 8.0, 727.2	6.0, 757.6 8.3, 751.6
19		rme - 3148, metabasite				6.0, 684.9 8.3, 688.9
20		rme - 3149, metabasite				6.0, 714.6 8.3, 730.0
21		rme - 3150, metabasite				6.0, 693.4 8.3, 700.9
22		rme - 3151, metabasite				6.0, 696.8 8.3, 708.2

GEOCHEMISTRY

In addition to the petrographic and geothermobarometric studies, whole rock geochemistry was done on samples from Timmins Creek area. The goal of this part of the research is to attempt to determine the protolith for these rocks. This is relevant as one of the purposes of this thesis is to shed light on the problem of the "Disappearance of the Huronian Supergroup" within the Grenville Front tectonic zone, which is a subject of long standing debate (see "Introduction").

Approximately 90 samples were analyzed in the Ontario Geoscience Laboratory, Sudbury, Ontario. Analytical methods used are described in Vander Voet and Riddle (1993) and Ontario Geological Survey Miscellaneous Paper 149, Volumes 1 and 2. For the purpose of discussing the results, the analyses are separated into three major groups: 1) mafic and 2) felsic igneous rocks (both intrusive and extrusive), as well as 3) schists and gneisses of sedimentary origin. In addition, a database of more than 150 geochemical analyses was compiled from the literature for the purpose of comparing Street Township rocks with possible correlative Proterozoic and Archean formations in the Sudbury area. These data were compiled from La Tour (1979), Kwak (1968), Pearson (1959), Card et al. (1977), Innes (1972, 1977) and Debicki (1990). Some samples collected and reported by Debicki (1990) were reanalysed for trace elements as part of this study. Representative analyses collected in this study are listed in Tables 4, 5 and 6. A compete listing of all newly acquired chemical data and data compiled from the literature is included in Easton and Murphy (in press).

Mafic Rocks

Based on the field description, four types of mafic rocks occur within the Timmins Creek and Street Township areas. They are 1) mafic volcanic rocks, 2) garnet-amphibolite gneisses, 3) Nipissing metagabbro, and 4) non-migmatized black amphibolites. Major element variation among these four groups is highlighted on an AFM diagram and a Jensen plot (Tables 4 and 5; Figure 24). Both Nipissing metagabbro and black amphibolite gneisses plot in the tholeiitic field in Figure 24a. This is a characteristic many of large diabase sills (Walker 1969, La Tour 1979) and mafic layered intrusions (Wager 1960). The mafic volcanic rocks and garnet-amphibolites also plot in the tholeiitic field in the AFM diagram and straddle the high-Fe tholeiite (HFT) and high-Mg tholeiite (HMT) fields in the Jensen plot (Figure 24b). On standard trace element discrimination plots (Figures 25 and 26) (e.g., Pearce and Cann 1973; Winchester and Floyd 1977; Wood 1980), all four groups of mafic rocks plot as tholeiites, either in the "plate margin basalt" or within "ocean floor basalt" fields.

Mafic volcanic rocks plotted in the AFM diagram show an Fe-enrichment trend and variation in Mg# from 35 to 48 (Figure 24). Garnet-amphibolite gneisses exhibit a less well-defined chemical variation. Distinction between the black amphibolites versus Nipissing metagabbro is based on Mg#. The high-Mg group includes black amphibolite as well as some rocks previously mapped as Nipissing (RME-0610). This group shows no Fe-enrichment with fractionation, but mainly enrichment in Al (Figure 24b). The low-Mg group includes only "Nipissing" amphibolite, which, in the field, can be recognized south of the Grenville Front boundary fault even when metamorphosed. This group shows iron-enrichment with fractionation (e.g., La Tour 1979). The degree of overlap and similar trends in AFM space may indicate the possibility of a genetic relationship between some of the Nipissing metagabbro and the black amphibolite gneisses. In addition, the garnet-amphibolite and mafic volcanic rocks display a similar possible genetic link. Investigation of REE patterns helps to test this possibility.

Table 4. Chemistry of mafic intrusive rocks.

Number	1	2	3	4	5	6
Unit	East Bull Lake intrusive suite amphibolites, Street Township			Nipissing gabbro suite		
Sample No.	96RME-0200	96RME-0457	96RME-0460	96RME-0610	96RME-3148	Avg. chill margin
Rock Type	Amphibolite	Amphibolite	Amphibolite	High Mg-gabbro	Gabbro	Chilled margin
Easting	529378	527405	527940	532053	533000	
Northing	5154410	5154410	5153600	5163742	5162870	
wt. %						
SiO_2	50.94	53.24	50.95	51.40	52.30	51.62
TiO_2	0.38	0.50	0.37	0.38	1.68	0.69
Al_2O_3	13.32	12.16	15.91	13.85	13.62	13.42
Fe_2O_3	0.45	1.40	1.25	1.78	3.17	11.83
FeO	6.85	7.60	6.10	6.20	10.00	
MnO	0.16	0.17	0.14	0.17	0.18	0.21
MgO	10.91	9.91	9.10	10.60	3.72	8.81
CaO	13.87	9.95	11.23	13.23	6.80	9.63
Na_2O	1.10	1.61	1.60	1.21	2.63	2.06
K_2O	0.45	0.85	0.75	0.34	2.20	0.73
P_2O_5	0.04	0.01	<0.01	<0.01	0.12	0.07
H_2O^-	0.12	0.14	0.17	0.20	0.33	0.13
CO_2	<0.01	0.10	0.09	0.11	0.15	0.24
S	0.02	<0.01	<0.01	0.01	0.02	0.08
LOI	0.69	0.65	0.69	0.38	1.88	1.81
Total	99.16	98.05	98.09	99.54	98.30	100.88
Mg #	72.82	66.59	69.18	70.77	34.03	59.59
ppm						
Cr	1134	830	760	740	17	
Ni	170	190	140	170	20	
Co	36	50	40	40	40	
Sc	40	28	24	35	27	
V	200	150	140	180	380	
Cu	68	54	52	58	20	
Zn	56	79	65	56	120	
Rb	8	17	24	10	65	
Ba	94	180	190	93	760	
Sr	98	140	170	120	190	
Nb	3	5.8	3	1.3	13	
Zr	32	96	62	36	200	
Y	13	22	16	13	43	
La	2.35	17.00	9.40	3.40	29.00	
Ce	5.62	33.00	19.00	7.60	62.00	
Pr	0.80	3.90	2.30	1.00	7.60	
Nd	3.62	15.00	9.00	4.40	29.00	
Sm	1.07	3.20	2.00	1.20	6.70	
Eu	0.36	0.78	0.64	0.40	1.90	
Gd	1.38	3.40	2.30	1.50	7.10	
Tb	0.24	0.56	0.35	0.25	1.20	
Dy	1.65	3.40	2.20	1.60	7.20	
Ho	0.36	0.72	0.45	0.36	1.50	
Er	1.05	2.10	1.40	1.10	4.40	
Tm	0.16	0.29	0.19	0.14	0.66	
Yb	1.01	2.00	1.30	1.00	4.30	
Lu	0.16	0.31	0.21	0.16	0.66	

Notes: Samples 1 to 5, this study, analyzed by the Geoscience Laboratories, Ontario Ministry of Northern Development and Mines; sample 6 *from* Lighfoot and Naldrett (1996).

Table 5. Chemistry of Huronian-age mafic extrusive and felsic intrusive and extrusive rocks.

Number	1	2	3	4	5	6	7	8	9	10	11
Unit			Stobie Formation					Copper Cliff Fm.		Granites	
Sample No.	86RLD-1902	96RME-0123	96RME-0447	96RME-3004	96RLD-0203	96RME-0124	96RME-0448	IN-CCF n=7	86RLD-5302	CW-MG28	IN-2
Rock Type	Basalt	Basalt	Basalt	Basalt	Dacite	Dacite	Dacite	Copper Cliff rhyolite	Copper Cliff rhyolite	Murray granite	Creighton granite
Easting		532820	532706	532009		532849	532820				
Northing		5162930	5162995	5162502		5162892	5162800				
wt. %											
SiO_2	46.35	54.75	49.20	50.62	69.69	66.42	61.58	75.24	75.46	73.37	75.90
TiO_2	1.02	0.75	1.04	2.17	0.62	0.72	1.22	0.15	0.15	0.37	0.33
Al_2O_3	17.24	14.87	13.93	13.74	12.30	12.95	12.48	13.29	11.75	12.87	12.40
Fe_2O_3	3.64	2.59	3.00	2.13	2.17	2.93	3.19	0.60	0.38		0.52
FeO	9.26	7.68	10.00	13.00	2.80	3.88	7.40	0.74	1.10	2.77	1.73
MnO	0.18	0.17	0.22	0.25	0.05	0.1	0.14	0.03	0.02	0.03	0.04
MgO	4.77	4.74	6.59	4.53	1.09	1.10	1.36	0.26	0.14	2.23	0.24
CaO	11.69	8.72	10.51	7.33	2.43	2.46	4.44	1.79	0.64	1.30	0.97
Na_2O	0.21	2.39	1.85	2.14	3.39	3.16	2.67	2.44	2.90	3.20	3.06
K_2O	0.31	1.30	0.52	0.95	2.99	3.57	3.08	3.89	5.28	5.83	5.30
P_2O_5	0.06	0.12	0.06	0.17	0.14	0.15	0.17	0.02	0.01	0.02	0.04
H_2O-	0.18	0.17	<0.01	<0.01	0.12	0.41	<0.01		0.08		
CO_2	0.70	0.18	0.14	0.14	0.23	0.15	0.10	0.10	0.34		
S	0.04	<0.01	0.08	0.21	<0.01	0.12	0.04	0.01	<0.01		
LOI	3.65	1.04	1.14	1.02	0.91	1.40	0.83	0.52	0.55		
Total	98.38	99.12	98.06	98.05	98.58	98.84	98.56	98.90	98.38	101.99	100.53
Mg #	40.4	45.8	48.0	35.1	29.0	23.1	19.1	25.0	14.8	58.9	16.3
Zr/Y	2.8	4.8	3.2	4.6	8.4	6.3	5.4	2.1	6.4		
ppm											
Cr	150	81	120	63	10	38	5		6		
Ni	70	78	81	73	11	16	9	10	<5		
Co	33	38	50	50	9	9	30	5	<5		
Sc	36	23	36	31	11	11	18		2		
V	330	155	290	370	38	28	95	10	<5		
Cu	160	78	150	290	55	9	10	19	15		
Zn	120	87	91	160	43	90	110	47	36		
Rb	9	41	16	28	110	96	99	206	210		
Ba	130	413	210	440	960	1070	880	558	900		
Sr	350	171	180	150	220	160	200	67	48		
Nb	4.6	10	5	12	14	23	20		31		
Zr	88	176	99	210	260	434	330		210		
Y	31	37	31	46	31	69	61		33		
Th	2	<10	2	11	11	18	15		38		
U	0.4	0	0.5	2.9	2.7	0	3.1		4.7		
Be	<3	<3			<3	<3			<3		
La	14.00	27.70	13.00	26.00	35.00	59.59	55.00		49.00		
Ce	27.00	57.45	28.00	57.00	75.00	146.86	110.00		96.00		
Pr	3.50	7.01	3.60	7.10	8.50	15.57	13.00		11.00		
Nd	15.00	26.30	15.00	27.00	34.00	58.67	51.10		36.00		
Sm	3.80	5.73	3.70	6.50	6.50	12.06	10.00		6.10		
Eu	1.50	1.33	1.10	1.60	1.50	2.30	2.20		0.79		
Gd	4.90	5.70	4.20	7.10	6.20	11.32	11.00		5.60		
Tb	0.78	0.95	0.72	1.20	0.96	1.88	1.70		0.93		
Dy	5.00	5.82	4.30	7.30	5.50	11.51	10.00		5.70		
Ho	1.00	1.23	0.95	1.60	1.10	2.48	2.10		1.20		
Er	3.10	3.56	2.80	4.60	3.40	7.37	6.20		4.60		
Tm	0.42	0.52	0.39	0.64	0.48	1.10	0.89		0.79		
Yb	2.60	3.30	2.50	4.20	3.10	6.77	5.60		6.10		
Lu	0.38	0.48	0.38	0.64	0.44	0.99	0.83		0.99		

Notes: Samples 1 to 7, 9, this study, analyzed by the Geoscience Laboratories, Ontario Ministry of Northern Development and Mines; sample 8, average of 7 samples (numbers 1, 29, 30, 32, 35, 36, 108) from Innes (1977); samples 10, 11; Innes (1977).

Table 5. continued.

Number	12	13	14	15	16	17	18	19	20	21
Unit	Street Township granitoids									
Sample No.	96RME-0049	96RME-0451	96RME-0454	96RME-0461	96RLD-0602	96RME-0606	96RME-3008	96RME-3022	96RME-03026	PW-1a
Rock Type	Granite gneiss	Granite	Granite gneiss	Granite	Granite gneiss	Granite	Granite	Granite gneiss	Granite gneiss	Granite gneiss
Easting	528569	532460	532620	528790	528806	532050	532021	531929	531849	
Northing	5153821	5162155	5162255	5154110	5154033	5162180	5162242	5161949	5161710	
wt. %										
SiO_2	70.61	71.07	69.25	68.37	69.88	67.59	69.56	66.98	71.00	70.25
TiO_2	0.33	0.34	0.34	0.62	0.53	0.70	0.60	0.82	0.34	0.41
Al_2O_3	12.31	12.28	12.40	12.54	12.15	12.55	11.83	12.13	12.09	11.91
Fe_2O_3	1.95	1.45	2.37	3.06	2.88	2.18	2.88	2.09	2.61	3.08
FeO	3.08	2.90	2.80	3.10	2.90	4.20	3.00	5.60	2.50	3.51
MnO	0.10	0.08	0.11	0.12	0.12	0.10	0.08	0.11	0.11	0.08
MgO	0.59	0.30	0.27	0.84	0.51	0.60	0.34	0.55	0.28	0.46
CaO	1.31	1.58	1.62	2.67	2.11	3.32	2.01	2.81	1.53	1.74
Na_2O	3.57	3.16	3.56	3.77	3.43	3.25	3.20	2.91	3.63	3.12
K_2O	3.91	4.74	4.94	3.77	4.13	3.60	4.13	3.53	4.46	4.84
P_2O_5	0.08	<0.01	0.01	0.18	0.08	0.11	0.04	0.14	0.02	0.20
H_2O-	0.19	0.21	0.19	0.19	0.17	0.18	0.19	0.16	0.17	0.04
CO_2	0.57	0.23	0.16	0.11	0.60	0.38	0.12	0.21	0.09	0.34
S	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	
LOI	1.07	0.56	0.37	0.31	0.35	0.86	0.37	0.53	0.35	
Total	98.91	98.46	98.04	99.35	99.07	99.06	98.04	98.20	98.92	99.60
Mg #	17.9	11.3	8.9	20.4	14.2	14.8	9.8	11.6	9.3	11.5
Zr/Y	7.4	7.5	6.3	6.7	5.9	6.6	7.2	6.1	6.4	
ppm										
Cr	22	6	6	3	3	4	3	4	7	
Ni	10	<5	<5	6	6	7	6	7	7	
Co	<5	<5	<5	10	<5	6	6	10	<5	
Sc	7	6	6	11	9	10	8	12	6	
V	12	6	7	20	20	10	6	10	6	
Cu	6	7	20	6	20	5	8	20	9	
Zn	142	110	160	100	120	42	83	110	140	
Rb	178	96	180	130	120	90	65	110	140	
Ba	1845	1100	1500	990	1300	970	1200	1100	1400	
Sr	120	140	120	210	140	160	130	150	110	
Nb	34	22	38	15	36	26	27	24	36	
Zr	733	490	690	280	650	440	480	420	640	
Y	99	65	110	42	110	67	67	69	100	
Th	19	19	20	13	19	19	21	19	19	
U		1.7	3.2	2.6	2.3	3.5	3.7	3.4	2.7	
Be	3	<3	3	<3	3	<3	<3	<3	3	
La	96.24	77	83	41	91	67	52	72	69	
Ce	382.73	>250	>250	95	>250	170	130	200	230	
Pr	25.7	19	22	11	23	16	13	17	18	
Nd	97.8	70	81	41	87	60	49	64	69	
Sm	20.10	13	17	8.9	18	12	10	13	16	
Eu	3.62	2.10	3.30	2.00	3.30	2.50	2.10	2.60	3.10	
Gd	19.56	13.00	18.00	8.50	18.00	12	11	13	16	
Tb	3.31	2.00	3.10	1.30	3.1	2	1.9	2.1	2.9	
Dy	19.87	11.00	19.00	7.60	18	11	12	12	18	
Ho	4.31	2.40	4.10	1.60	3.9	2.4	2.6	2.6	4	
Er	12.69	7.00	12.00	4.60	12	6.9	7.8	7.6	12	
Tm	1.93	0.97	1.80	0.63	1.7	0.98	1.2	1.1	1.9	
Yb	12.61	6.40	12.00	4.10	11	6.3	7.7	7	12	
Lu	1.98	0.93	1.90	0.60	1.7	0.95	1.1	1.1	1.8	

Notes: Samples 12 to 20, this study, analyzed by the Geoscience Laboratories, Ontario Ministry of Northern Development and Mines; sample 21, Pearson (1959).

Table 6. Whole rock chemistry of Huronian Supergroup metasedimentary rocks with the Sudbury area.

Sample No.	Source	Easting	Northing	Rock Type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3
McKim Formation								
MFY-1	McLennan et al. 1978	Espanola		McKim composite	59.66	0.75	20.27	6.90
86RLD-5501	this study*	Sudbury		McKim wacke	85.20	0.26	6.31	0.58
96RME-0499	this study	491500	5146000	McKim metapelite	55.65	0.96	22.99	0.90
Metaconglomerate								
96RME-3005	this study	531950	5162255	conglomerate	56.09	1.30	14.41	1.02
Pecors Formation								
MFY-2	McLennan et al. 1978	Espanola		Pecors composite	60.76	0.77	19.36	6.60
CID-P1	Card et al. 1977	Sudbury		siltstone	62.60	0.93	19.60	0.42
86RLD-3703	this study*	Sudbury		Pecors siltstone	62.09	0.83	17.72	1.72
86RLD-5102	this study*	Sudbury		Pecors siltstone	64.79	0.70	15.51	1.08
96RME-0234	this study	531930	5162020	TC schist	64.01	0.86	16.19	1.46
96RME-0242	this study	531900	5161900	ky schist	60.86	0.99	17.67	1.19
Mississagi Formation								
86RLD-0402	this study*	Sudbury		Miss. subarkose	85.69	0.15	6.48	0.51
86RLD-0801	this study*	Sudbury		Miss. arkose	76.60	0.26	9.49	2.67
86RLD-0805	this study*	Sudbury		Miss. subarkose	86.61	0.12	6.95	0.46
86RLD-0905	this study*	Sudbury		Miss. wacke	87.20	0.18	6.40	0.61
96RME-3001	this study	531359	5162477	Miss. sandstone	82.99	0.31	6.72	0.66
96RME-0092	this study	531060	5162100	Miss. siltstone	77.65	0.36	9.34	1.10
96RME-0122	this study	532680	5163500	schist	85.05	0.17	6.99	1.17
96RME-3040	this study	532900	5162310	schist	82.52	0.15	7.11	0.64
96RME-0183	this study	527529	5154663	bi-ky schist	59.19	1.29	17.52	0.78
96RME-0184	this study	527529	5154663	meta-arenite	73.82	0.46	12.38	0.65
96RME-0185	this study	527560	5154760	granetite	52.65	2.11	14.38	3.55
96RME-3015	this study	531800	5162012	breccia	61.02	1.05	15.04	1.23
Atypical Mississagi Formation								
86RLD-3902	this study*	Sudbury		Miss. siltstone	59.04	0.75	20.85	2.06
96RME-3030	this study	531960	5162357	schist	72.23	0.63	10.63	1.34
96RME-3031	this study	531900	5162260	schist	59.21	1.03	15.32	1.68
96RME-3032	this study	532200	5162530	schist	66.77	0.85	12.81	2.09
Bruce Formation								
86RLD-1104	this study*	Sudbury		Bruce wacke	64.80	0.58	13.79	1.63
96RME-3002	this study	531359	5162477	siltstone	68.98	0.56	12.61	1.41
Espanola Formation								
86RLD-1701	this study*	Sudbury		Espanola siltstone	64.29	0.41	12.95	0.79
86RLD-2904	this study*	Sudbury		Espanola siltstone	61.73	0.06	15.01	1.76
86RLD-3408	this study*	Sudbury		alt Espanola arkose	41.50	0.53	11.37	0.68
Serpent Formation								
86RLD-3002	this study*	Sudbury		Serpent arkose	75.57	0.11	11.52	0.39
Garnet-Biotite Schists and Gneisses within the Grenville Province								
96RME-3023	this study	531919	5161912	paragneiss	56.59	0.90	16.20	1.82
96RME-3028	this study	531983	5161597	paragneiss	76.56	0.28	11.94	1.03
95RME-0136	this study	530135	5158632	gt schist	56.26	1.01	16.77	2.98
95RME-0137	this study	530253	5159057	gt-musc schist	51.73	0.96	17.53	6.80
95RME-0138	this study	530253	5159057	musc schist	79.36	0.30	10.42	0.93
95RME-0150	this study	529636	5157943	gt-musc schist	51.80	1.38	19.06	5.92
95RME-0151	this study	529636	5157943	gt-bi-musc schist	55.28	0.69	16.41	2.87
96RME-0064	this study	527000	5154020	gt-bi gneiss	58.75	0.76	15.18	3.55
96RME-0068	this study	527000	5154020	gt-bi gneiss	61.04	1.19	12.76	2.46

Table 6. continued.

Sample No.	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^-	CO_2	S	LOI	Total
McKim Formation												
MFY-1	0.00	0.06	2.27	0.87	1.49	3.36	0.08				4.46	100.17
86RLD-5501	1.40	<0.01	1.34	0.24	2.09	0.41	<0.01	0.09	0.20	0.02	1.12	98.97
96RME-0499	5.60	0.04	2.21	0.87	1.00	3.60	0.04	0.42	0.26	0.07	4.28	98.21
Metaconglomerate												
96RME-3005	8.60	0.08	3.75	2.61	2.72	2.88	0.22	0.27	0.12	0.02	3.87	97.57
Pecors Formation												
MFY-2	0.00	0.05	2.58	0.63	1.54	3.90	0.10				3.92	100.21
CID-P1	5.35	0.07	3.40	1.01	1.20	2.17	0.08	0.12	0.12			96.83
86RLD-3703	4.10	0.04	2.72	1.07	1.36	4.34	0.03	0.13	0.01	0.46	2.73	99.21
86RLD-5102	4.60	0.04	2.94	1.10	1.72	2.47	0.03	0.10	0.01	0.07	2.69	97.74
96RME-0234	4.50	0.07	2.34	1.98	2.87	2.50	0.10	0.28	0.11	<0.01	1.23	98.11
96RME-0242	6.30	0.07	3.32	1.31	1.70	2.85	0.12	0.30	0.16	0.02	1.35	97.75
Mississagi Formation												
86RLD-0402	0.64	<0.01	0.93	0.05	2.73	0.46	<0.01	0.06	0.06	0.07	0.78	98.49
86RLD-0801	0.40	<0.01	0.78	0.07	3.72	1.41	<0.01	0.31	0.20	<0.01	1.22	96.62
86RLD-0805	0.40	<0.01	0.52	0.06	3.03	0.78	<0.01	0.11	0.33	0.06	0.66	99.65
86RLD-0905	0.44	<0.01	0.56	0.16	1.24	1.88	0.02	0.05	0.10			98.69
96RME-3001	2.20	<0.01	1.76	0.09	2.59	0.01	<0.01	0.21	0.11	0.08	1.43	98.84
96RME-0092	2.34	<0.01	1.60	0.11	1.94	2.36	0.04	0.34	0.18	0.14	1.79	98.77
96RME-0122	0.60	<0.01	0.88	0.03	0.59	2.42	0.03	0.39	0.13	0.02	1.61	99.56
96RME-3040	0.54	<0.01	0.75	0.02	1.17	2.35	<0.01	0.28	0.16	0.03	3.50	98.78
96RME-0183	6.49	0.08	2.11	0.95	2.50	5.75	0.20	0.17	0.14	<0.01	0.70	97.56
96RME-0184	2.72	0.04	0.91	0.72	2.70	4.08	0.07	0.14	0.14	<0.01	0.48	99.03
96RME-0185	11.29	0.33	3.77	8.93	0.18	0.71	0.63	0.25	0.12	0.07	0.64	99.24
96RME-3015	7.00	0.10	3.15	2.39	2.66	2.89	0.15	0.26	0.10	0.05	1.02	97.75
Atypical Mississagi Formation												
86RLD-3902	1.20	0.02	1.98	0.35	0.72	7.97	<0.01	0.20	0.20	0.01	3.12	98.07
96RME-3030	3.80	0.03	2.39	0.91	1.24	3.13	0.10	0.34	0.38	0.01	1.54	97.98
96RME-3031	7.00	0.09	3.06	2.50	2.95	3.40	0.15	0.31	0.22	0.05	1.31	97.75
96RME-3032	5.50	0.07	1.34	0.76	3.68	3.25	0.12	0.40	0.33	0.01	1.27	98.52
Bruce Formation												
86RLD-1104	4.00	0.04	3.55	1.86	4.12	2.21	0.05	0.16	0.34	0.15	1.10	97.88
96RME-3002	3.50	0.02	3.35	0.08	1.47	2.50	0.04	0.49	0.21	0.01	3.82	98.35
Espanola Formation												
86RLD-1701	2.60	0.02	3.28	3.36	6.02	0.35	0.04	0.06	2.60	0.17	3.78	98.06
86RLD-2904	3.50	<0.01	4.74	0.46	6.59	1.92	0.06	0.11	0.44	0.19	1.19	97.21
86RLD-3408	2.50	0.08	6.70	11.64	6.68	0.09	0.04	0.10	17.00	0.06	17.39	99.26
Serpent Formation												
86RLD-3002	0.81	<0.01	1.40	0.63	4.79	1.88	<0.01	0.09	0.71	<0.01	1.31	98.41
Garnet-Biotite Schists and Gneisses within the Grenville Province												
96RME-3023	5.80	0.07	3.41	1.84	1.45	4.31	0.12	0.36	2.40	0.09	5.34	97.94
96RME-3028	1.40	0.02	1.02	0.41	1.18	3.36	0.01	0.18	0.12	<0.01	1.64	98.85
95RME-0136	11.81	0.21	3.11	2.28	2.58	1.37	0.18	0.12	0.09	0.08	0.01	98.65
95RME-0137	15.35	0.30	1.31	2.18	0.03	1.82	0.04	0.14	0.15	1.09	0.02	99.16
95RME-0138	2.54	0.02	0.60	0.41	0.13	2.70	0.04	0.14	0.68	0.13	2.10	99.68
95RME-0150	13.85	0.20	1.79	0.98	0.13	2.26	0.10	0.16	0.09	0.16	0.22	97.85
95RME-0151	16.16	0.27	2.00	2.04	1.30	1.18	0.04	0.12	0.13	0.45	0.01	98.70
96RME-0064	8.02	0.49	2.23	5.58	2.29	1.37	0.37	0.22	0.15	0.02	0.73	99.35
96RME-0068	9.88	0.19	2.15	4.13	1.64	2.01	0.23	0.23	<0.10	0.04	0.48	98.20

Table 6. continued.

Sample No.	CIA	PIA	Mg #	Cr	Ni	Co	Sc	V	Cu	Pb	Zn	Rb	Cs	Ba
McKim Formation														
MFY-1	77.99		39.45											
86RLD-5501	71.30	73.47	55.41	76	30	<5	5	41	70	23	25	19	1.10	190
96RME-0499	81.52	92.33	38.06	190	84	30	20	170	67	23	110	160	4.00	760
Metaconglomerate														
96RME-3005	64.04	68.88	41.25	86	60	30	14	170	50	18	120	100	9.80	1000
Pecors Formation														
MFY-2	76.13		43.64											
CID-P1	82.15		51.40	250	70	20	20	100	50	30	100			500
86RLD-3703	72.39	84.68	46.19	260	110	32	19	160	100	19	94	140	9.30	1500
86RLD-5102	74.60	82.27	48.46	230	90	24	15	120	38	40	110	93	2.70	680
96RME-0234	69.10	74.28	41.77	120	50	20	12	120	40	23	75	97	6.90	1100
96RME-0242	75.61	83.87	44.53	210	58	20	16	140	30	22	100	110	6.50	880
Mississagi Formation														
86RLD-0402	67.08	68.88	60.13	51	9	<5	3	20	<5	26	16	19	0.25	130
86RLD-0801	65.49	69.24	33.15	46	30	<5	4	36	35	49	13	42	0.93	280
86RLD-0805	66.25	69.09	53.24	34	18	<5	2	16	19	43	10	32	0.77	220
86RLD-0905	66.81		50.23											
96RME-3001	72.26	72.31	52.89	120	40	10	4	30	30	<7	20	7	0.27	58
96RME-0092	68.83	78.87	46.13	47	50	12	4	44	47	<7	31	86		454
96RME-0122	70.61	90.32	48.69	44	12	4	3	26	16	8	16	72		281
96RME-3040	67.78	82.21	54.50	40	10	<5	3	20	10	<7	10	69	1.10	330
96RME-0183	65.91	78.05	34.33	90	50	25	17	150	8	16	89	189		1671
96RME-0184	62.72	71.68	32.92	27	14	9	5	31	4	9	30	99		1102
96RME-0185	59.72	60.33	31.69	71	5	6	3	21	4	14	16	20		136
96RME-3015	65.73	71.05	40.91	170	73	30	16	150	40	16	120	100	5.90	1100
Atypical Mississagi Formation														
86RLD-3902	70.23	93.67	53.61	210	21	<5	15	140	15	46	30	700	4.20	1600
96RME-3030	68.45	80.91	45.97	41	30	10	8	82	9	12	68	97	8.00	1900
96RME-3031	63.97	69.50	39.05	140	54	29	16	170	40	16	120	110	3.00	1500
96RME-3032	63.51	69.93	24.44	61	20	9	13	30	9	14	110	150	25.00	1200
Bruce Formation														
86RLD-1104	63.72	67.25	53.64	220	59	19	13	120	32	8	54	92	2.40	60
96RME-3002	76.66	88.30	55.59	210	30	<5	14	120	20	<7	40	92	2.70	330
Espanola Formation														
86RLD-1701	64.49	65.02	63.84	100	52	21	9	73	6	<7	16	27	0.90	74
86RLD-2904	63.76	66.45	62.43	130	92	19	15	130	8	<7	21	160	4.20	270
86RLD-3408	88.97	89.52	79.32	130	42	<5	12	88	8	23	20	5	0.06	47
Serpent Formation														
86RLD-3002	63.61	67.18	68.24	34	15	<5	2	18	5	9	10	45	0.84	480
Garnet-Biotite Schists and Gneisses within the Grenville Province														
96RME-3023	75.70	93.04	51.16	150	85	30	17	140	81	16	130	170	6.10	750
96RME-3028	71.20	85.37	56.49	9	20	7	5	40	7	12	35	140	6.10	790
95RME-0136	73.20	76.35	27.66	145	66	44	27	196	114	12	110	54		809
95RME-0137	81.88	88.41	9.81	186	97	57	28	188	228	17	96	64		894
95RME-0138	80.28	101.85	24.05	32	21	10	5	37	37	-7	23	85		661
95RME-0150	85.32	94.28	14.26	99	67	49	33	305	79	13	67	69		1595
95RME-0151	78.89	82.59	15.98	183	81	48	41	143	248	12	70	52		553
96RME-0064	62.55	64.14	26.16	16	20	26	18	49	100	17	66	70		785
96RME-0068	62.12	65.07	24.06	24	22	22	20	37	72	13	171	97		1148

Table 6. continued.

Sample No.	Sr	Ta	Nb	Hf	Zr	Y	Th	U	La	Ce	Pr	Nd	Sm
McKim Formation													
MFY-1									29.00	67.00		29.00	5.70
86RLD-5501	57	0.34	3.1	3.2	130	6	17.0	3.3	6.10	13.00	1.40	4.82	0.82
96RME-0499	280	0.97	11.0	4.7	170	31	20.0	6.0	51.00	100.00	11.00	41.00	7.50
Metaconglomerate													
96RME-3005	760	0.83	15.0	3.7	220	24	7.8	1.2	45.00	95.00	11.00	41.00	7.70
Pecors Formation													
MFY-2									36.00	82.00		34.00	6.40
CID-P1	300				120								
86RLD-3703	200	0.71	9.3	3.6	150	22	8.6	2.9	26.00	55.00	6.60	25.00	4.80
86RLD-5102	140	0.87	10.0	5.1	200	20	12.0	4.5	33.00	67.00	7.90	29.00	5.20
96RME-0234	600	0.50	5.9	4.0	190	17	8.1	2.5	40.00	83.00	9.50	34.00	5.80
96RME-0242	250	0.41	5.2	4.8	180	33	9.4	3.3	41.00	87.00	10.00	38.00	6.80
Mississagi Formation													
86RLD-0402	57	0.06	0.6	1.2	55	8	3.9	1.1	8.40	18.00	2.20	8.10	1.40
86RLD-0801	58	0.31	3.4	2.6	120	9	4.8	1.1	5.40	15.00	1.50	5.40	1.20
86RLD-0805	89	0.14	1.5	0.9	43	6	1.9	0.7	3.60	8.00	0.95	3.70	0.70
86RLD-0905													
96RME-3001	53	0.12	1.4	1.7	120	10	4.8	1.9	5.30	12.00	1.50	5.70	1.20
96RME-0092	70		5.0		65	6	<10.0		2.09	4.86	0.60	2.21	0.45
96RME-0122	28		3.0		63	7	<10.0		4.42	10.11	1.18	4.26	0.74
96RME-3040	43	0.31	2.7	1.2	56	8	3.6	2.0	9.40	20.00	2.40	8.90	1.60
96RME-0183	148		19.0		364	39	15.0		56.99	123.56	15.53	57.95	10.80
96RME-0184	133		8.0		216	21	<10.0		33.58	74.55	9.04	33.53	6.02
96RME-0185	125		13.0		225	57	<10.0		35.64	79.97	10.46	43.33	10.17
96RME-3015	380	0.73	12.0	3.9	190	20	8.8	2.4	46.00	93.00	11.00	40.00	7.00
Atypical Mississagi Formation													
86RLD-3902	60	1.60	15.0	4.2	170	12	9.2	7.4	1.70	7.70	0.64	2.70	0.79
96RME-3030	310	0.61	9.5	3.8	170	11	7.0	1.5	9.30	22.00	1.90	6.40	1.10
96RME-3031	380	0.77	13.0	1.6	180	17	7.7	1.3	18.00	28.00	2.90	9.60	1.70
96RME-3032	200	1.60	27.0	13.0	460	35	14.0	3.4	23.00	66.00	5.90	22.00	4.60
Bruce Formation													
86RLD-1104	230	0.54	6.8	3.4	140	11	7.7	1.9	10.00	24.00	3.10	12.00	2.30
96RME-3002	38	0.24	3.1	2.9	160	13	6.6	3.7	19.00	43.00	5.20	20.00	3.70
Espanola Formation													
86RLD-1701	110	0.32	2.8	3.8	150	20	9.3	3.5	35.00	67.00	7.80	29.00	5.00
86RLD-2904	89	1.00	12.0	5.1	180	22	15.0	5.4	6.40	18.00	2.10	8.60	2.20
86RLD-3408	49	0.25	3.1	3.3	120	14	9.1	2.9	3.20	7.00	0.95	4.30	1.20
Serpent Formation													
86RLD-3002	190	0.16	1.6	1.0	48	9	2.0	0.7	30.00	64.00	7.90	29.00	4.20
Garnet-Biotite Schists and Gneisses within the Grenville Province													
96RME-3023	110	0.37	3.4	4.6	160	29	11.0	2.6	43.00	88.00	10.00	38.00	7.10
96RME-3028	86	0.54	6.1	2.0	90	10	6.2	2.1	27.00	55.00	6.20	21.00	3.20
95RME-0136	56		12.0		216	49	<10.0		30.12	62.65	7.97	30.76	6.85
95RME-0137	12		9.0		183	53	<10.0		27.76	56.78	7.11	27.90	6.63
95RME-0138	14		4.0		99	12	<10.0		15.47	31.60	3.72	13.32	2.39
95RME-0150	12		21.0		467	112	92.0		289.95	500.02	77.22	291.88	49.65
95RME-0151	59		7.0		473	86	<10.0		18.59	37.64	4.61	17.25	3.80
96RME-0064	182		8.0		348	90	48.0		47.62	161.94	10.68	36.67	6.76
96RME-0068	144		20.0		370	67	22.0		44.64	99.12	11.74	44.72	9.87

Table 6. continued.

Sample No.	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
McKim Formation									
MFY-1	1.50	5.10		4.60		2.70			
86RLD-5501	0.12	0.71	0.10	0.64	0.13	0.44	0.06	0.53	0.09
96RME-0499	1.70	6.70	0.98	5.20	0.94	2.70	0.34	2.50	0.38
Metaconglomerate									
96RME-3005	2.10	6.70	0.94	4.80	0.85	2.50	0.31	2.10	0.31
Pecors Formation									
MFY-2	1.60	5.50		4.50		2.70			
CID-P1									
86RLD-3703	1.30	4.60	0.68	3.90	0.77	2.30	0.34	2.20	0.33
86RLD-5102	1.20	4.50	0.65	3.50	0.69	2.10	0.30	2.10	0.32
96RME-0234	1.70	4.80	0.64	3.20	0.55	1.60	0.20	1.40	0.22
96RME-0242	1.70	5.70	0.78	4.00	0.68	2.00	0.26	1.90	0.29
Mississagi Formation									
86RLD-0402	0.21	1.10	0.13	0.60	0.09	0.28	0.04	0.31	0.04
86RLD-0801	0.42	1.20	0.20	1.30	0.25	0.72	0.10	0.74	0.10
86RLD-0805	0.22	0.73	0.07	0.54	0.10	0.35	0.04	0.36	0.05
86RLD-0905									
96RME-3001	0.25	1.10	0.14	0.79	0.15	0.51	0.06	0.54	0.09
96RME-0092	0.16	0.42	0.07	0.44	0.09	0.28	0.04	0.32	0.05
96RME-0122	0.23	0.55	0.07	0.42	0.08	0.24	0.03	0.28	0.05
96RME-3040	0.45	1.20	0.17	0.79	0.11	0.34	0.04	0.37	0.06
96RME-0183	2.35	8.53	1.23	6.23	1.28	3.76	0.57	3.80	0.59
96RME-0184	1.57	4.55	0.64	3.34	0.70	2.09	0.31	2.00	0.31
96RME-0185	3.05	10.37	1.66	9.73	2.00	5.52	0.78	4.97	0.76
96RME-3015	1.80	6.00	0.83	4.20	0.74	2.20	0.30	1.90	0.30
Atypical Mississagi Formation									
86RLD-3902	0.56	1.00	0.19	1.60	0.40	1.50	0.28	2.10	0.34
96RME-3030	0.80	1.00	0.18	1.20	0.28	1.10	0.18	1.40	0.21
96RME-3031	0.89	1.40	0.25	1.80	0.55	2.10	0.33	2.30	0.34
96RME-3032	1.20	4.60	0.80	5.30	1.20	4.00	0.65	4.80	0.81
Bruce Formation									
86RLD-1104	0.62	1.80	0.27	1.60	0.32	1.10	0.16	1.20	0.19
96RME-3002	0.83	2.80	0.34	1.50	0.24	0.82	0.10	0.87	0.16
Espanola Formation									
86RLD-1701	0.87	4.00	0.52	2.50	0.47	1.50	0.23	1.60	0.24
86RLD-2904	0.79	2.60	0.47	3.40	0.71	2.30	0.33	2.20	0.34
86RLD-3408	0.35	1.50	0.23	1.40	0.26	0.81	0.12	0.93	0.14
Serpent Formation									
86RLD-3002	0.82	2.80	0.32	1.20	0.19	0.53	0.06	0.50	0.08
Garnet-Biotite Schists and Gneisses within the Grenville Province									
96RME-3023	1.60	5.80	0.69	2.70	0.33	0.94	0.09	0.67	0.11
96RME-3028	0.87	2.50	0.34	1.50	0.21	0.70	0.07	0.53	0.09
95RME-0136	1.63	7.40	1.28	8.09	1.68	4.95	0.73	4.76	0.75
95RME-0137	1.60	8.47	1.47	9.39	1.84	5.18	0.73	4.68	0.69
95RME-0138	0.60	1.75	0.22	0.90	0.16	0.43	0.07	0.47	0.08
95RME-0150	5.01	33.02	3.92	17.20	3.50	10.27	1.52	10.30	1.56
95RME-0151	1.12	7.40	1.75	13.72	3.02	9.11	1.37	8.82	1.34
96RME-0064	1.46	8.06	1.62	12.55	3.30	11.24	1.85	12.94	2.15
96RME-0068	1.81	10.36	1.80	11.41	2.44	7.08	1.05	6.69	1.03

Table 6. continued.

Sample No.	Source	Location	Rock Type	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO
Additional Garnet-Biotite and Garnet-Kyanite Schists and Gneisses									
K120	Kwak 1967	Dill Twp	schist	53.53	2.15	26.80	1.78	3.98	0.06
K150	Kwak 1967	Dill Twp	schist	47.45	1.40	23.20	1.56	9.76	0.18
K156A	Kwak 1967	Dill Twp	schist	66.35	1.31	17.20	1.74	4.02	0.06
K156B	Kwak 1967	Dill Twp	schist	63.70	1.59	21.60	1.92	2.84	0.02
K231	Kwak 1967	Dill Twp	schist	57.50	1.38	22.84	1.33	5.52	0.09
K232B	Kwak 1967	Dill Twp	schist	63.95	1.22	18.81	1.06	4.64	0.05
K232C	Kwak 1967	Dill Twp	schist	60.95	1.23	19.90	1.88	3.24	0.05
K249	Kwak 1967	Dill Twp	schist	61.30	1.25	20.80	0.84	5.64	0.04
K290	Kwak 1967	Dill Twp	schist	69.65	1.51	16.25	2.20	3.72	0.07
K292	Kwak 1967	Dill Twp	schist	57.20	1.04	20.80	1.09	6.28	0.09
K293	Kwak 1967	Dill Twp	schist	53.60	1.46	21.50	1.32	10.60	0.11
K296	Kwak 1967	Dill Twp	schist	53.90	1.04	17.60	1.80	15.80	0.16
K78	Kwak 1967	Dill Twp	schist	58.80	1.23	23.36	1.70	6.24	0.08
K79	Kwak 1967	Dill Twp	schist	60.95	1.81	19.87	1.45	5.92	0.08
PW216	Pearson 1959	Dryden Twp	gneiss	76.25	0.46	10.90	0.62	2.32	0.03
PW217	Pearson 1959	Dryden Twp	gt gneiss	82.55	0.24	8.20	0.71	1.21	0.03
PW218	Pearson 1959	Dryden Twp	gt gneiss	61.96	0.62	16.10	0.87	5.80	0.14
PW219	Pearson 1959	Dryden Twp	ky gneiss	60.90	1.56	23.00	1.09	4.84	0.03
PW220	Pearson 1959	Dryden Twp	ky gneiss	64.82	1.45	12.60	1.20	10.20	0.18
PW221	Pearson 1959	Dryden Twp	quartzite	90.39	0.27	3.10	0.51	1.40	0.02
PW222	Pearson 1959	Dryden Twp	gneiss	70.14	0.36	14.00	0.64	3.12	0.09
PW223	Pearson 1959	Dryden Twp	gt gneiss	71.12	0.45	13.01	0.69	4.00	0.17
PWVa	Pearson 1959	Dryden Twp	ky gneiss	54.64	0.78	25.36	0.98	7.16	0.07
PWVb	Pearson 1959	Dryden Twp	ky gneiss	56.67	0.55	25.16	0.42	6.53	0.07
Elsie Mountain Formation									
CID-EM3	Card et al. 1977	Sudbury	st metapelite	57.38	1.00	25.33	1.13	4.86	0.05
CID-EM4	Card et al. 1977	Sudbury	st metapelite	59.40	1.17	23.10	1.10	4.19	0.04
CID-EM5	Card et al. 1977	Sudbury	metapelite	59.30	1.25	21.80	0.46	5.42	0.06
CID-EM6	Card et al. 1977	Sudbury	st-bi metapelite	61.48	0.88	21.77	2.64	4.10	0.06
CID-EM7	Card et al. 1977	Sudbury	metapelite	54.40	1.21	16.30	2.77	7.89	0.13
Stobie Formation									
CID-ST10	Card et al. 1977	Sudbury	metapelite	58.40	1.52	12.40	2.92	8.39	0.15
CID-ST11	Card et al. 1977	Sudbury	metapelite	58.40	1.40	15.70	3.71	2.97	0.15
CID-ST12	Card et al. 1977	Sudbury	metapelite	56.60	1.27	19.80	3.17	5.42	0.06
CID-ST13	Card et al. 1977	Sudbury	metapelite	56.10	1.39	24.50	1.95	3.96	0.03
Additional McKim Formation Samples									
CID-MK1	Card et al. 1977	Sudbury	metapelite	55.07	0.98	21.50	2.72	6.04	0.05
CID-MK2	Card et al. 1977	Sudbury	metapelite	60.73	0.74	21.18	3.23	4.16	0.04
CID-MK3	Card et al. 1977	Sudbury	metapelite	57.14	0.71	25.61	2.33	4.17	0.05
CID-MK4	Card et al. 1977	Sudbury	sandstone	57.75	0.82	19.19	2.98	7.86	0.07
CID-MK5	Card et al. 1977	Sudbury	metapelite	62.00	0.64	18.90	1.24	4.24	0.05
CID-MK6	Card et al. 1977	Sudbury	metapelite	54.60	0.96	23.90	1.32	5.20	0.04
CID-MK7	Card et al. 1977	Sudbury	metapelite	55.55	0.84	22.80	1.40	5.28	0.09
CID-MK8	Card et al. 1977	Sudbury	metapelite	60.40	0.98	22.40	4.11	3.97	0.06
CID-MK9	Card et al. 1977	Sudbury	greywacke	65.60	0.79	16.30	0.74	5.45	0.07
IN-MK13	Innes 1972	Sudbury	pelite	57.17	0.82	25.38	0.70	5.25	0.07
IN-MK14	Innes 1972	Sudbury	schist	58.14	0.80	23.99	0.00	4.53	0.06

Table 6. continued.

Sample No.	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^-	CO_2	S	LOI	Total	CIA	Mg #
Additional Garnet-Biotite and Garnet-Kyanite Schists and Gneisses												
K120	2.80	0.81	0.88	5.17	0.16	0.22				98.12	79.62	47.20
K150	4.40	2.95	3.15	3.89	0.44	0.10	0.11			98.38	70.13	41.26
K156A	2.80	0.83	0.53	3.59	0.09	0.15				98.52	77.65	47.18
K156B	2.27	1.09	1.03	2.50	0.07	0.21				98.63	82.38	46.97
K231	3.44	1.10	1.00	3.31	0.16	0.20				97.67	80.85	47.72
K232B	2.67	1.36	1.07	3.18	0.02	0.21				98.03	77.03	45.96
K232C	2.60	1.49	2.27	3.74	0.10	0.24				97.45	72.63	48.44
K249	2.16	1.04	1.35	2.72	0.11	0.30				97.25	80.28	37.57
K290	1.96	0.94	0.65	2.13	0.04	0.19				99.12	81.37	38.00
K292	3.48	1.28	2.56	4.75	0.10	0.08				98.67	70.77	46.07
K293	2.99	1.94	2.29	2.77	0.10	0.07	0.02			98.68	75.49	31.13
K296	3.49	1.76	1.49	2.05	0.11	0.08				99.20	76.86	26.31
K78	2.89	0.76	0.83	3.12	0.14	0.06				99.15	83.22	39.86
K79	2.70	1.49	1.78	2.69	0.17	0.09				98.91	76.93	39.97
PW216	0.92	1.25	2.47	2.75		0.08	0.01			97.97	62.79	36.29
PW217	0.31	0.89	1.66	2.72		0.08	0.33			98.52	62.40	23.01
PW218	1.93	1.59	3.00	5.75		0.12	0.09			97.76	61.10	34.32
PW219	1.66	0.30	0.48	4.84		0.06	0.14			98.70	80.76	33.70
PW220	2.06	4.01	0.47	1.35		0.10	0.12			98.34	68.81	24.55
PW221	0.30	0.30	1.57	0.53		0.06	0.11			98.39	57.51	22.34
PW222	3.40	0.30	2.32	4.17		0.13	0.11			98.54	67.70	62.11
PW223	1.27	1.36	2.35	3.50		0.12	0.08			97.92	64.60	32.88
PWVa	2.54	1.57	1.11	3.81	0.04	0.13	0.80			98.06	81.67	36.01
PWVb	2.94	0.78	1.95	3.28	0.05	0.09	0.61			98.40	82.33	43.13
Elsie Mountain Formation												
CID-EM3	2.48	0.34	2.08	2.01	0.11	0.07	0.64			96.77	86.98	42.92
CID-EM4	1.58	0.59	1.30	4.59	0.10	0.55	1.06			97.16	81.00	35.21
CID-EM5	2.05	0.90	1.56	4.13	0.10	0.13	0.08			97.03	77.00	38.51
CID-EM6	2.74	1.39	1.32	2.20	0.12	0.07	0.53			98.70	83.25	42.99
CID-EM7	4.83	2.19	3.04	1.34	0.14	0.03	0.05			94.24	71.43	45.33
Stobie Formation												
CID-ST10	3.10	6.53	1.85	1.04	0.17	0.12	0.10			96.47	57.09	33.40
CID-ST11	1.37	4.77	4.25	1.98	0.05	0.30	0.15			94.75	59.13	27.90
CID-ST12	2.50	1.18	2.07	3.69	0.12	0.23				95.88	74.05	35.00
CID-ST13	1.42	0.68	2.20	5.29	0.10	0.10	0.10			97.62	75.22	30.69
Additional McKim Formation Samples												
CID-MK1	3.00	0.98	1.43	3.01	0.11	0.02	0.12			94.89	80.22	38.65
CID-MK2	2.75	0.79	0.90	2.30	0.09		0.20			96.91	84.82	40.95
CID-MK3	2.39	1.01	1.01	2.66	0.09		0.12			97.17	84.89	40.46
CID-MK4	2.44	2.27	2.34	0.98	0.11	0.02	0.02			96.81	77.50	29.20
CID-MK5	3.30	1.64	2.17	1.88	0.11	0.05				96.17	76.86	52.34
CID-MK6	3.60	0.82	0.90	4.12	0.18	0.04				95.64	80.36	50.11
CID-MK7	3.20	0.56	0.72	4.65	0.15	0.07				95.24	79.36	46.58
CID-MK8	2.77	0.01	0.86	2.54	0.08	0.12	0.18			98.18	87.40	39.16
CID-MK9	2.67	0.89	1.41		0.12	0.26	0.04			94.04	87.82	43.76
IN-MK13	2.46	0.26	1.66	2.59	0.29	0.08	0.74		3.52	100.17	87.07	42.71
IN-MK14	2.11	0.17	0.75	4.82	0.30	0.09	1.11		3.07	98.74	83.82	45.36

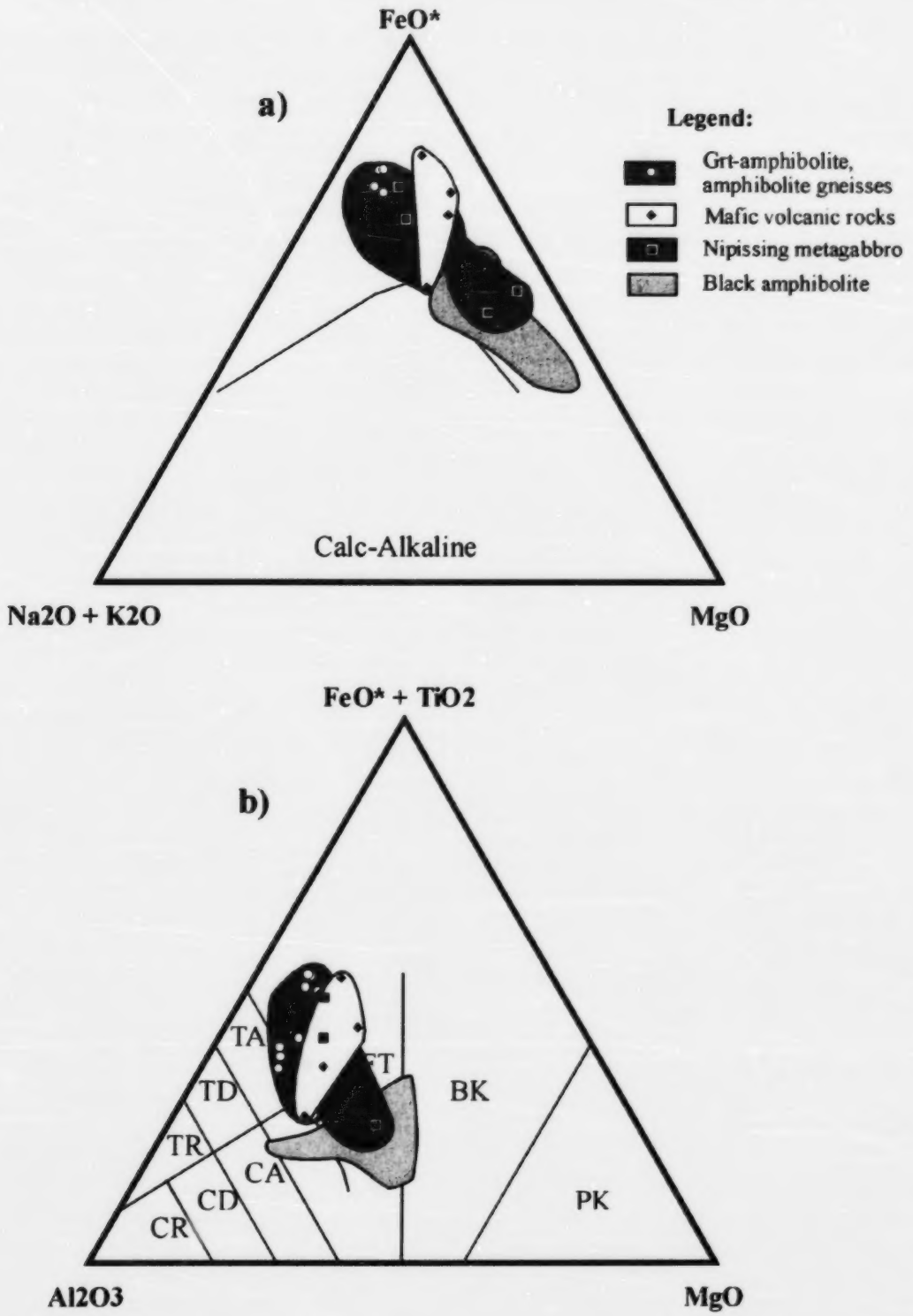


Figure 24. Chemical variation of mafic rocks from the Timmins Creek area on the diagrams of a) Irvine and Baragar (1971), and b) Jensen (1976).

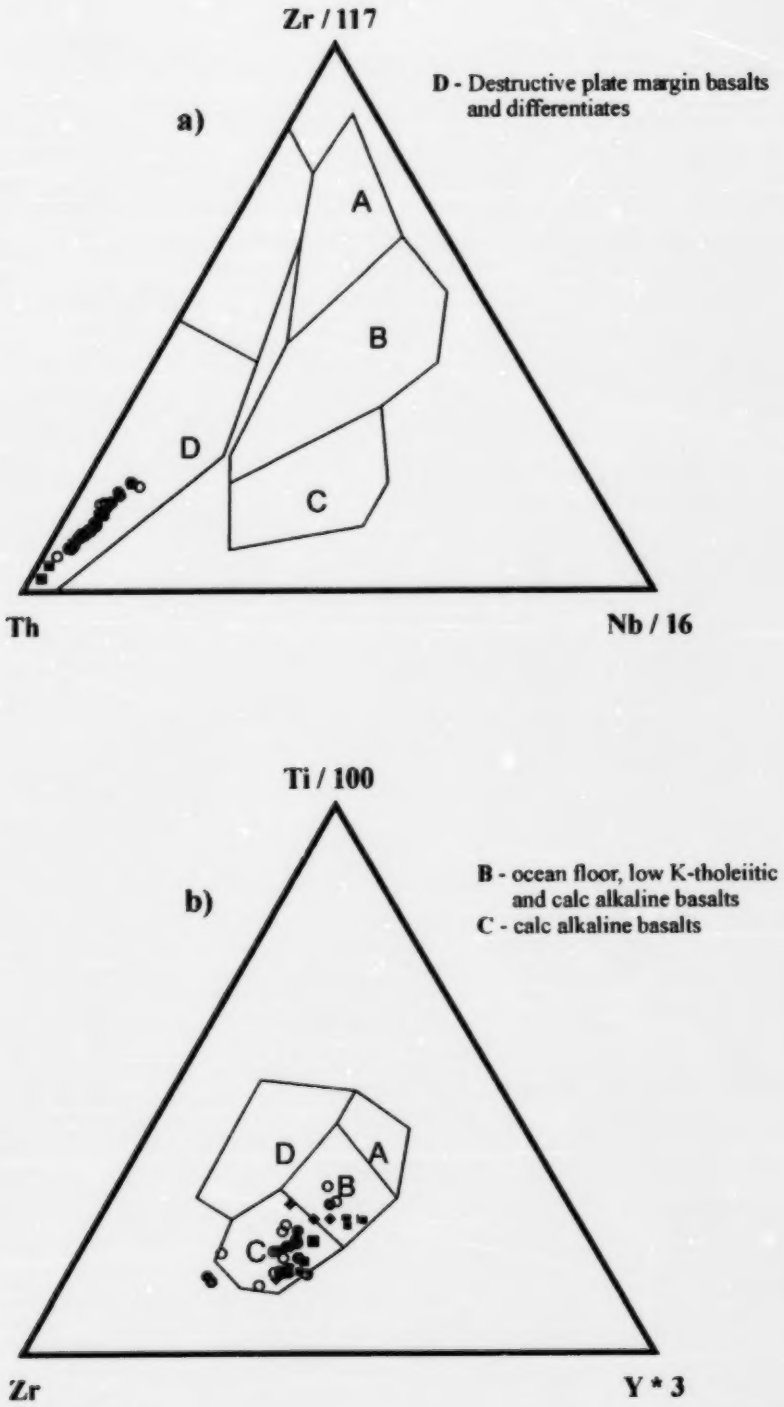


Figure 25. Chemical variation of mafic rocks from the Timmins Creek area on the trace element discrimination diagrams of a) Wood (1980), and b) Pearce and Cann (1973). Plotted samples are garnet-amphibolite and amphibolite gneisses (●), mafic metavolcanic rocks (◆), Nipissing metagabbro (○), and black amphibolites (■).

All mafic rocks show patterns of LREE-enrichment, and exhibit a narrow range in La/Yb values from 1.6 to 6.1 (Figures 27 and 28). Garnet-amphibolite gneisses and mafic volcanic rocks have similar REE patterns (Figure 27), generally with higher total REE than the black amphibolite group (Figure 28). In general, all individual samples form subparallel patterns, with the largest diversity occurring in the LREE. All mafic rocks have a negative Eu anomaly. The average value Eu/Eu* = 0.72.

Field subdivision between black amphibolite and Nipissing metagabbro is not straightforward. This is also observed in the geochemical majors, trace and REE data. Figure 27 shows two separate groups of REE patterns. These distinct groups correspond to black amphibolite and some Nipissing metagabbro gneisses. The latter shows a pattern of LREE-enrichment, with La/Yb values ranging from 3.7 to 5.7 and a weak Eu anomaly. In contrast, the black amphibolite samples show a flat REE pattern, La/Yb equals 2.0 and little or no Eu anomaly. Based on available major and trace element geochemistry, black amphibolite and Nipissing metagabbro gneisses may simply represent variation between more and less primitive parts of Nipissing diabase sills. Black amphibolites have Mg# = 70. These are thought to be derived from pyroxene-enriched phases of the Nipissing diabase. Nipissing metagabbro gneisses with Mg# = 62 or less are the metamorphic equivalent of the norite/gabbro facies of the Nipissing metagabbro gneiss. It is also possible that high Mg# black amphibolite is related to mafic norite/gabbro of the layered River Valley intrusion. Further attempts to separate these two rock types geochemically are beyond scope of this thesis.

A comparison using major and trace elements was done to test correlation between mafic volcanic rock from the study area and existing data for Huronian mafic volcanic rocks (Stobie, Elsie Mountain). One available REE analysis on a mafic Stobie volcanic rock displays a similar REE patterns with the Timmins Creek mafic volcanic rocks (Figure 29). In the AFM space and on a Jensen diagram, all samples (Stobie, Elsie Mountain and Timmins Creek mafic volcanic rocks) plot in relatively the same area (Figures 30, 31).

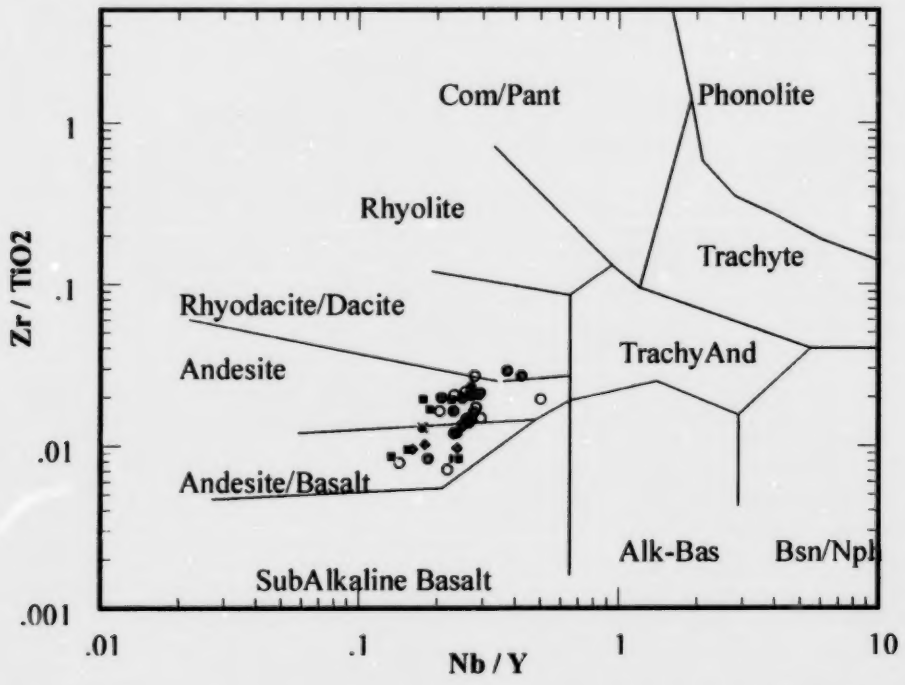


Figure 26. Chemical variation of mafic rocks from the Timmins Creek area on the trace element distribution diagram of Winchester and Floyd (1977). See Figure 25 for symbols.

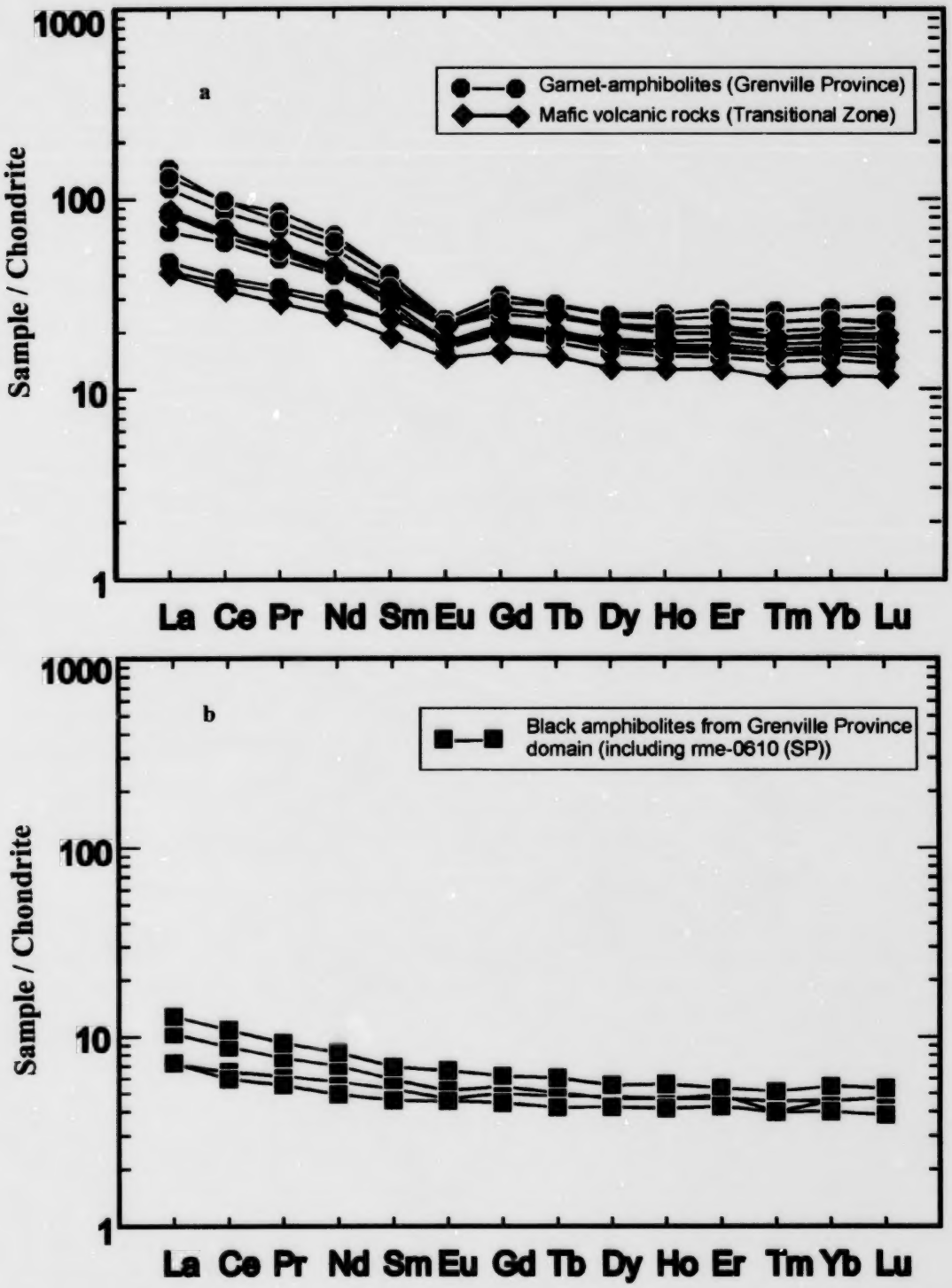


Figure 27. REE patterns for a) garnet-amphibolite gneisses and mafic metavolcanic rocks; and b) black amphibolites in Street Township.

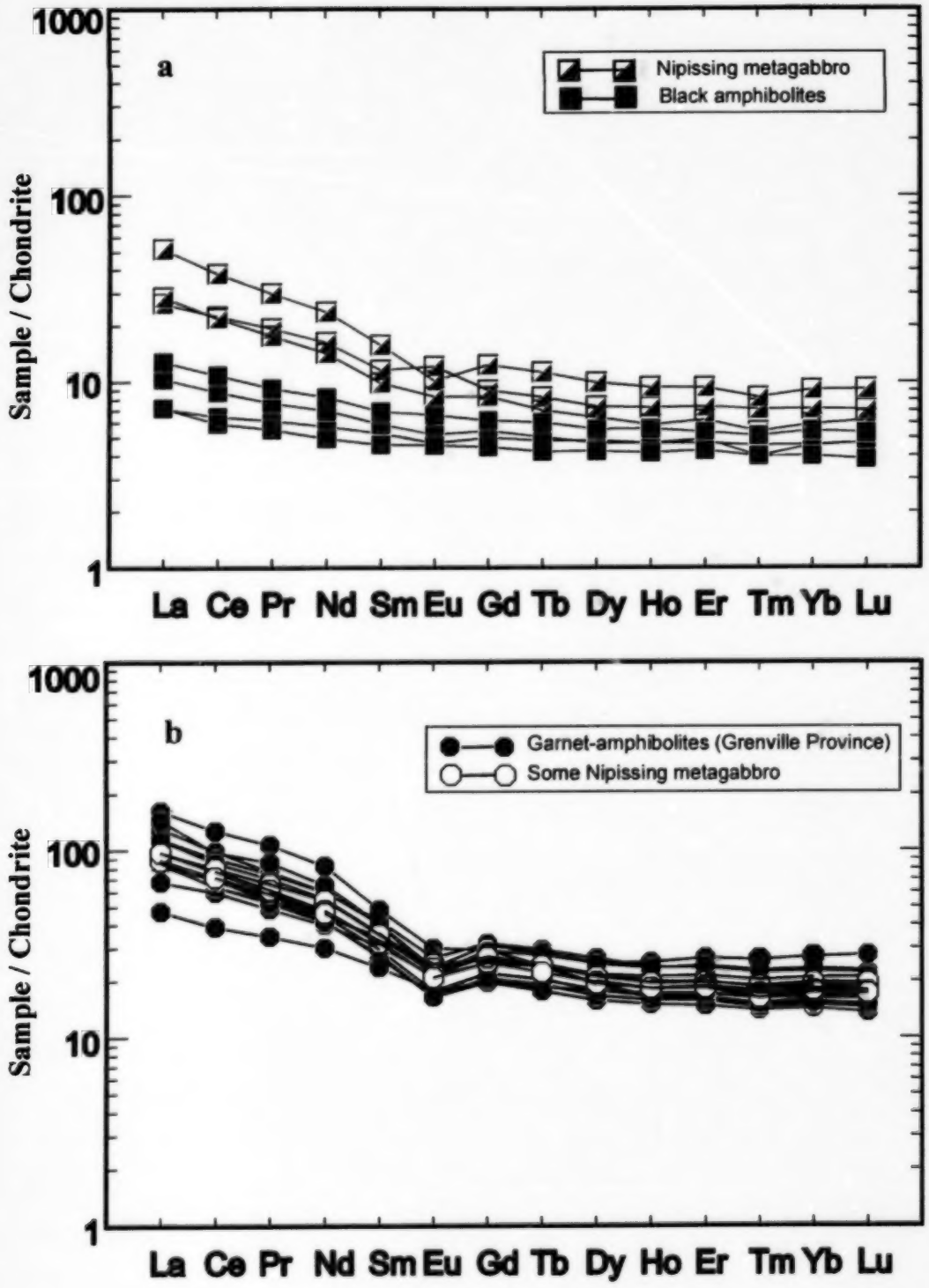


Figure 28. REE patterns for a) black amphibolites and Nipissing metagabbro; and b) amphibolites (Nipissing metagabbro) and garnet-amphibolites in Street Township.

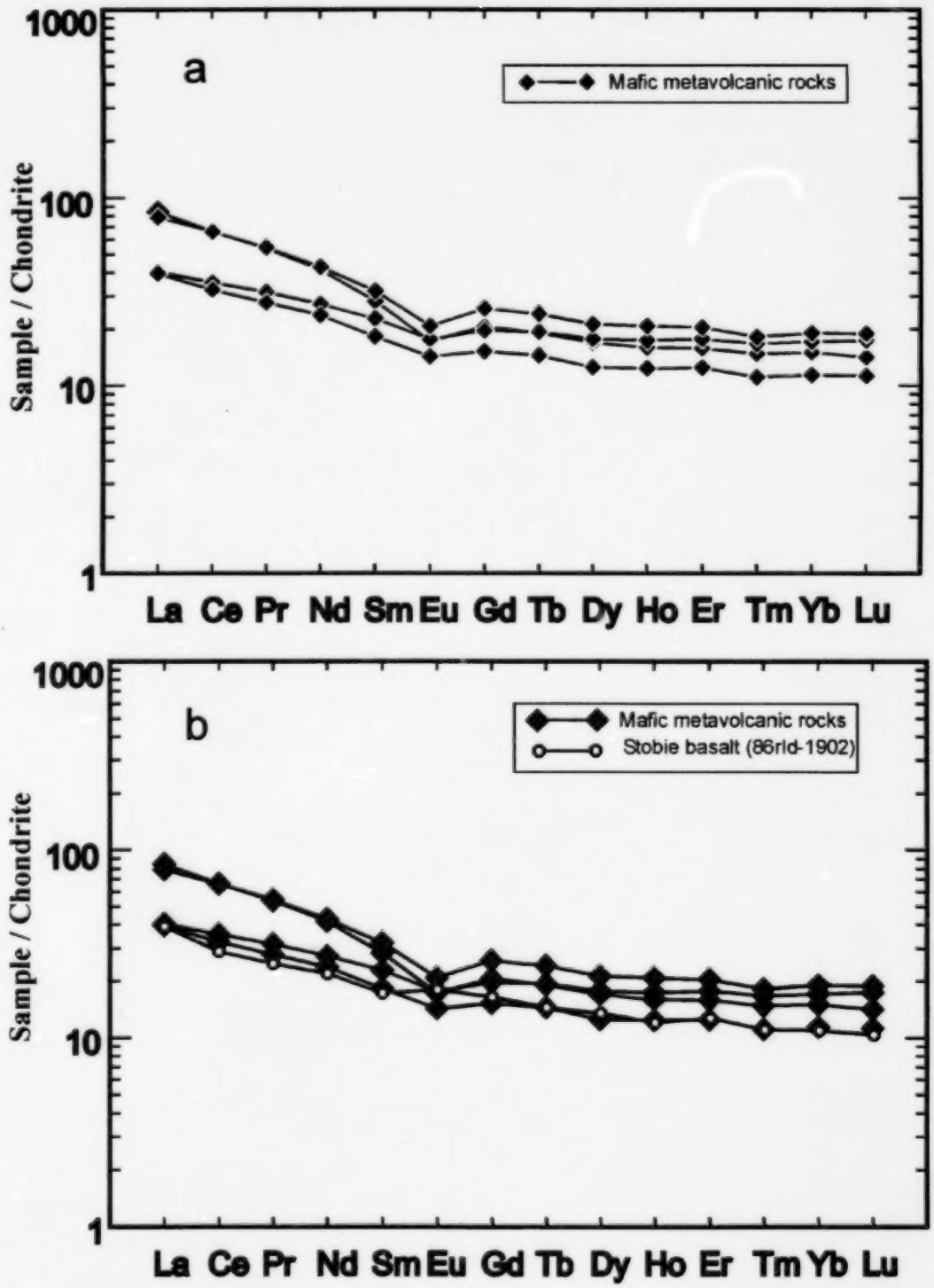


Figure 29. REE patterns for a) metavolcanic rocks from the Transitional Zone, Timmins Creek area. b) The same as (a), but also including a Stobie Formation basalt sample *from* Debicki (1990).

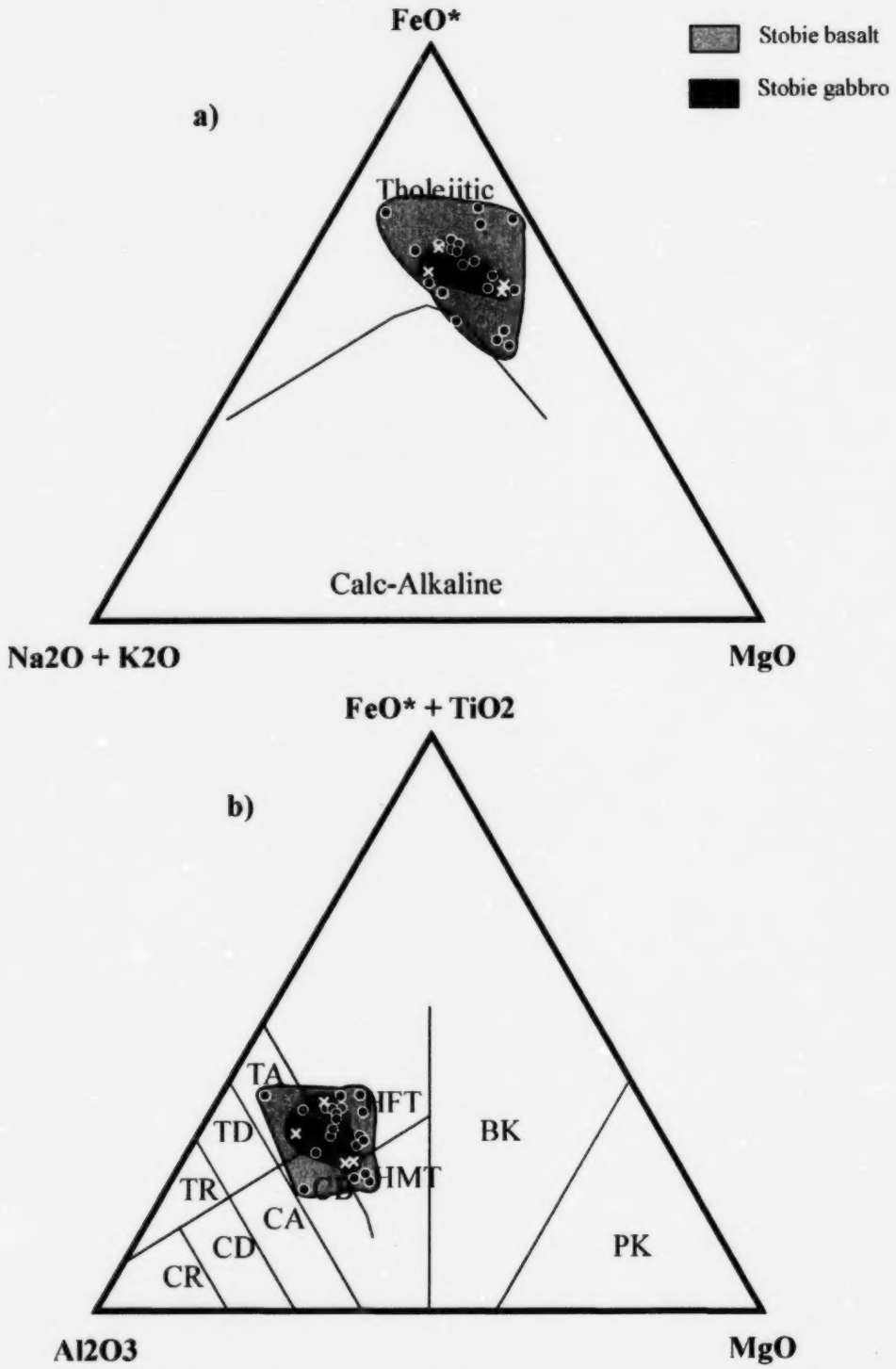


Figure 30. Chemical variation of Stobie gabbro and Stobie Formation basalt on the diagrams of a) Irvine and Baragar (1971), and b) Jensen (1976).

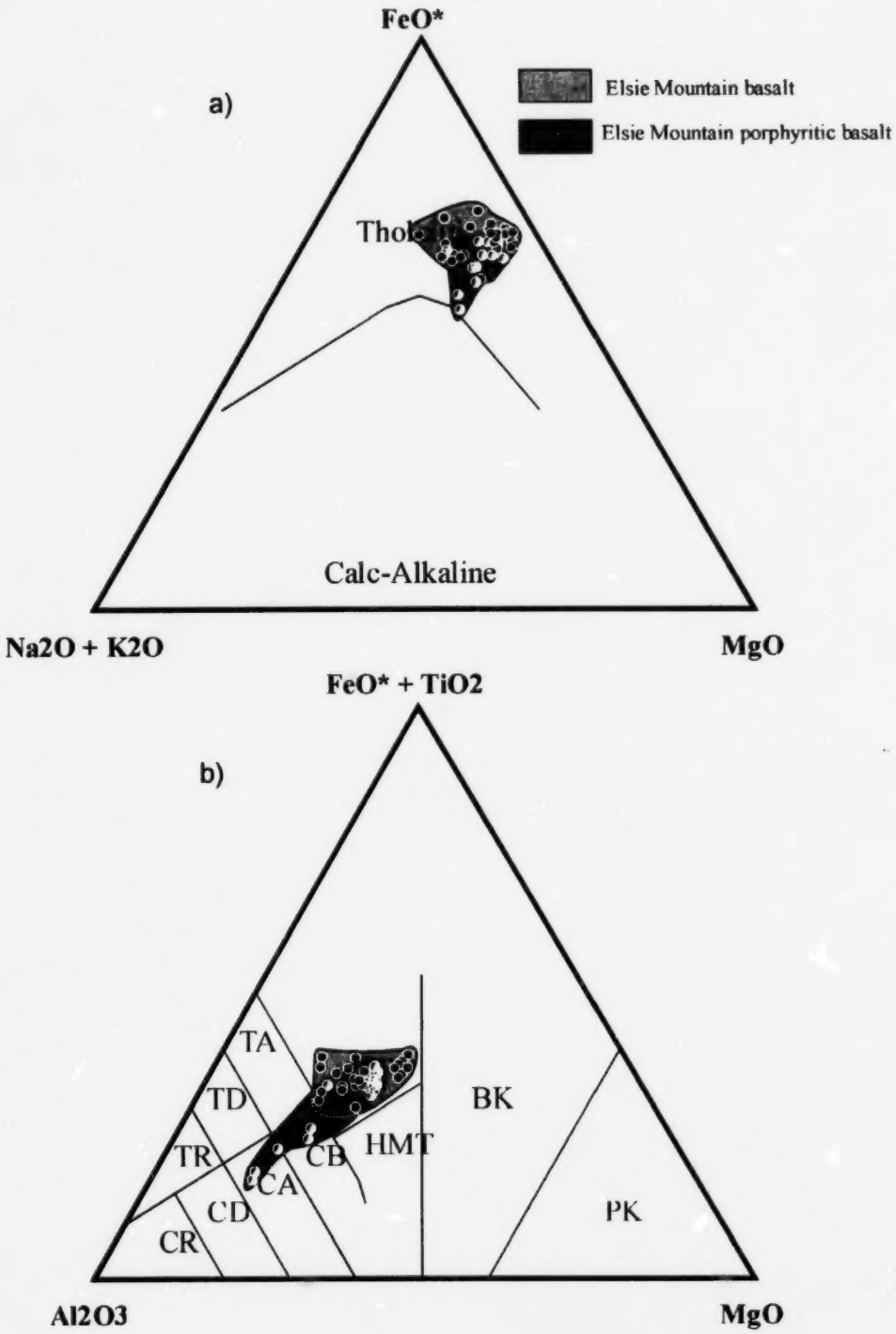


Figure 31. Chemical variation of Elsie Mountain Formation basalt and porphyritic basalt on the diagram of a) Irvine and Baragar (1971), and b) Jensen (1976).

There is no apparent reason to dispute Lumbers' (1973) suggestion that the Timmins Creek mafic volcanic rocks correspond to the base of the Mississagi Formation of the Huronian Supergroup. This conclusion is based on geochemical similarities between Timmins Creek mafic volcanic rocks and Stobie Formation, and is also consistent with presence of felsic volcanic rocks in the study area. The stratigraphic position of sheared rocks of Mississagi Formation (rme-3040, rme-0122) (discussed below) against mafic Timmins Creek volcanic rock is in agreement with this correlation and suggests that a portion of the upper Elliot Lake Group and lower Hough Lake Group stratigraphy is missing in this area.

Felsic volcanic and granitic rocks

Geochemical interpretations are based on 9 analyses from different granitic bodies from both sides of the Grenville Front boundary fault and two samples from the felsic volcanic rocks in the Timmins Creek area. These data are presented in Table 5. Geochronology has been done on the granitic bodies, which are foliated and non-migmatized north of the Grenville Front boundary fault, and migmatized and well folded on its south side. Both granites have U/Pb zircon ages of circa 2460 Ma (Corfu and Easton, in press), and so there is no doubt that they are the same rocks.

On the classification normative Q-A-P composition diagram (after Streckeisen 1976), most Street Township felsic rock samples plot in the "monzogranite" field, and only two plot in the "granodiorite" field (Figure 32). In a Y + Nb versus Rb trace element diagram (Pearce et al. 1984), Street Township felsic rocks plot mainly in the "within plate granites" field (rifting environment); one sample falls in the "volcanic arc granites" field (Figure 33).

On an AFM and a Jensen diagram, the felsic rocks from Street Township form two distinct groups. Both lie in the tholeiitic field on the AFM diagram (Figure 34). This distinguishes them from felsic rocks that occur in Sudbury area (Murray and Creighton granites and Copper Cliff rhyolites). The latter plot in the calc-alkaline field in both the AFM and Jensen space (Figure 35). Data for the Timmins Creek felsic rocks form clusters on those diagrams, whereas scatter characterizes the Copper Cliff rhyolite, Murray and Creighton granite data.

The monzogranites on both side of the Grenville Front boundary fault have very similar major and trace element geochemistry (Table 5). Their REE patterns show LREE-enrichment and negative Eu anomalies (La/Yb = 5.8, Gd/Yb = 1.3, Eu/Eu* = 0.59). The felsic metavolcanic rocks from the Timmins Creek area have similar REE patterns. These volcanic rocks occur at the same stratigraphic level as the Timmins Creek mafic volcanic rocks, which are probably correlative with the Stobie Formation (Figure 36). The geochemical similarities suggest that the granites in the Timmins Creek area are likely subvolcanic equivalents of the Timmins Creek felsic volcanic rocks. Therefore, these volcanic rocks are likely to be the same initial age as the granitic rocks, that is, circa 2460 Ma, which best estimates the age of the Stobie Formation (the minimum age of the Copper Cliff rhyolite is circa 2450 Ma (Krogh et al. 1984)).

Based on REE patterns of the felsic rocks and La/Yb =5.8; Gd/Yb =1.3; Eu/Eu* =0.59 values, these Timmins Creek felsic rocks are FIII-type rhyolite. This rhyolite type has been used as a positive indicator in base metal exploration (e.g., Lesher et al. 1986; Parker and Ayer 1997).

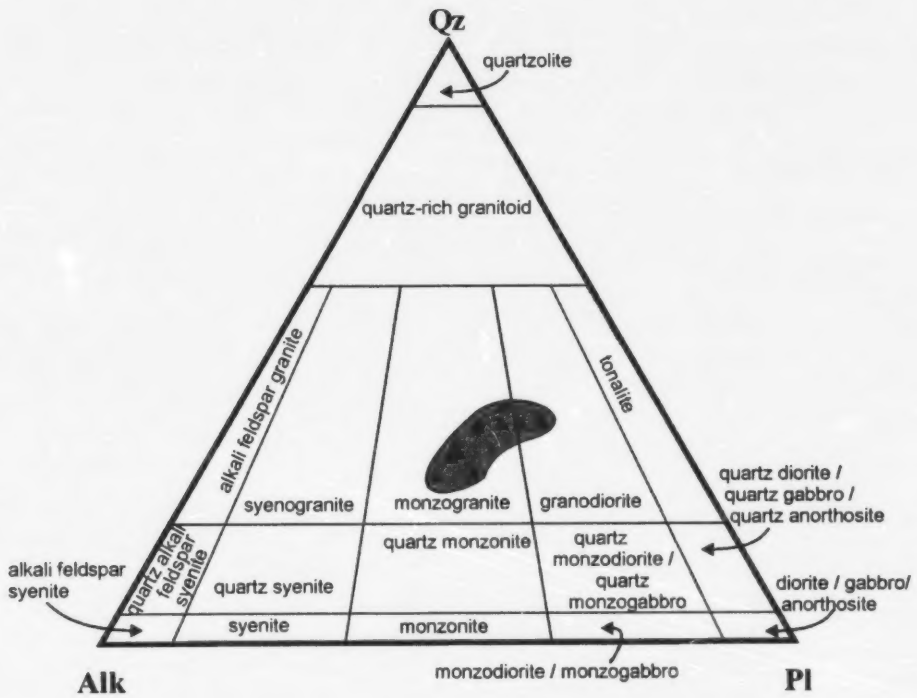


Figure 32. Geochemically derived modal composition of granite (▲) and felsic metavolcanic rocks (◆) from the Timmins Creek area, on the Streckeisen (1976) diagram.

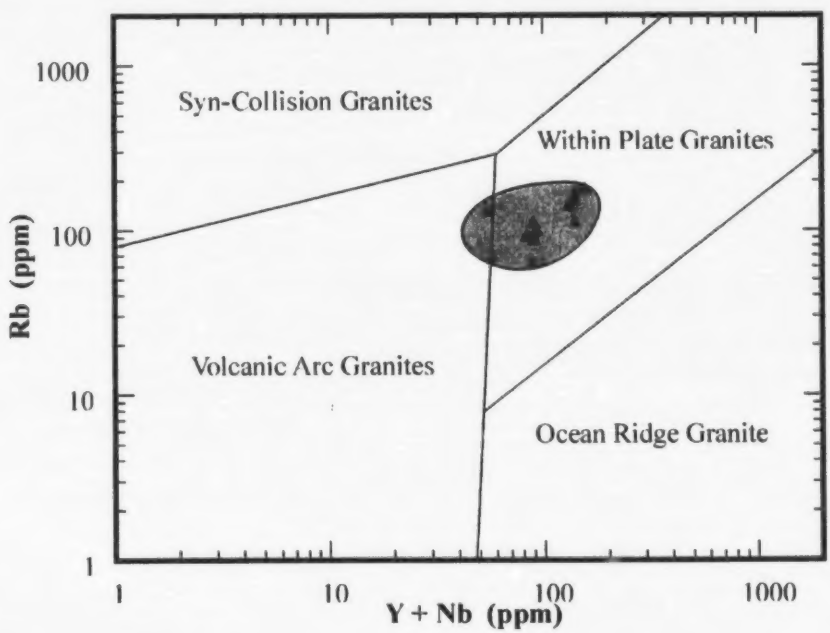


Figure 33. Chemical variation of granite (▲) and felsic metavolcanic rocks (◆) from the Timmins Creek area, on the diagram by Pearce et al. (1984).

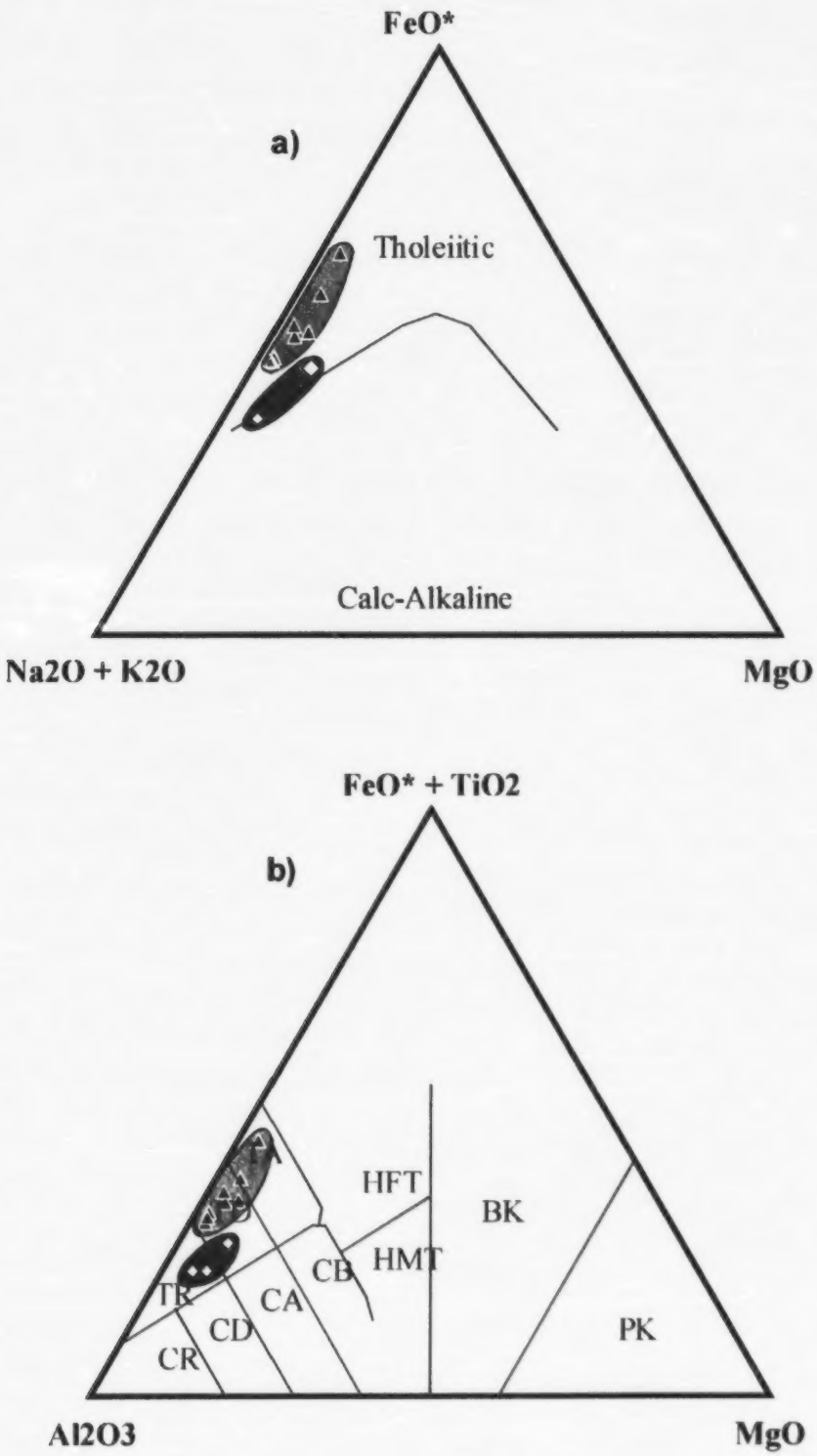


Figure 34. Chemical variation of granitic (▲) and felsic metavolcanic (◊) rocks from the Timmins Creek area, on the diagrams of a) Irvine and Baragar (1971), and b) Jensen (1976).

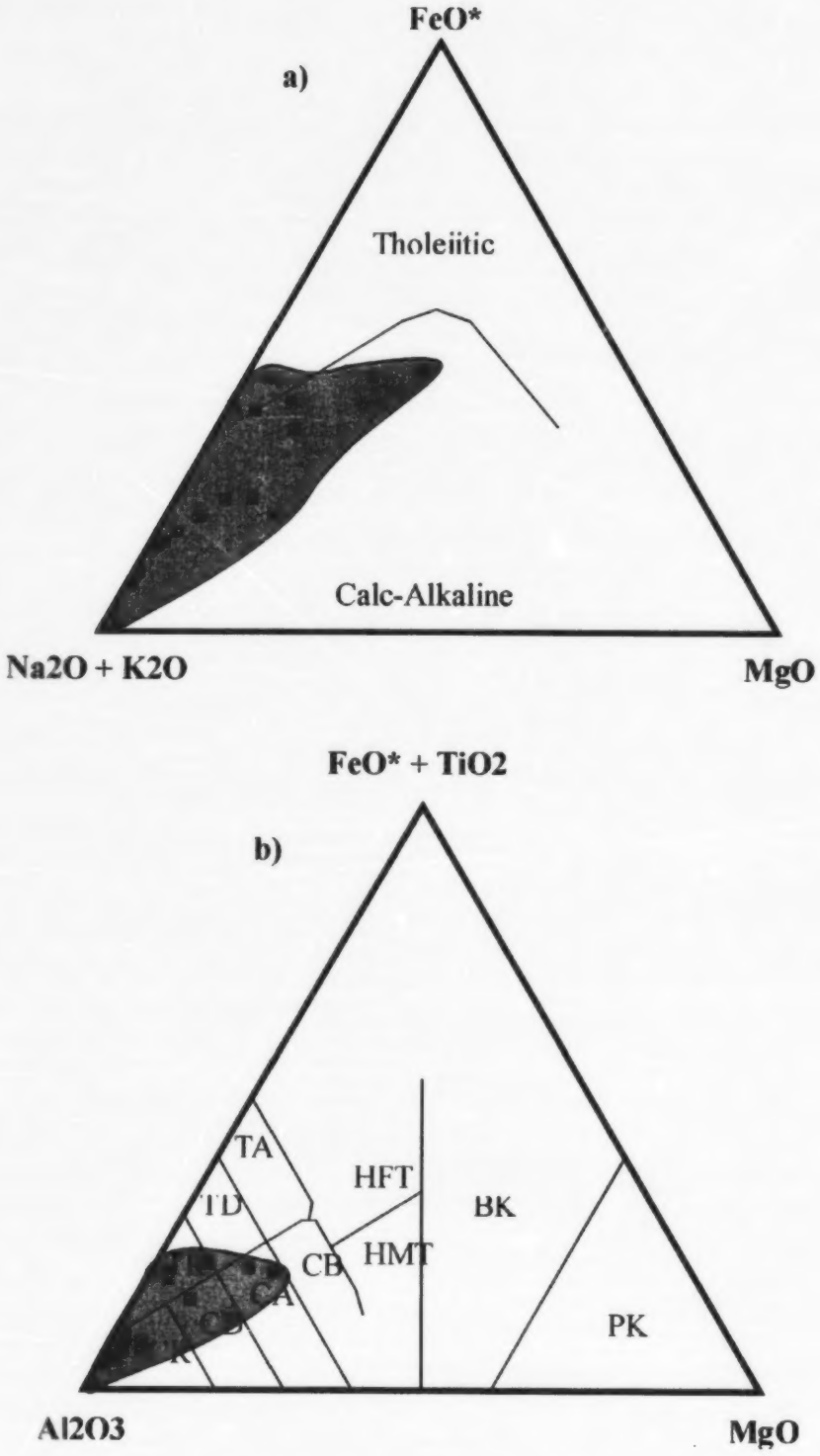


Figure 35. Chemical variation of Copper Cliff rhyolites (■) and Murray and Creighton granites (×) on the diagrams of a) Irvine and Baragar (1971), and b) Jensen (1976).

Pelitic rocks

Based on the major, trace and REE geochemistry, the Timmins Creek pelitic rocks can be represented as three separate groups. On AFM and Jensen diagrams, pelitic rocks define two fields (Figure 37). The first field is for samples from the Mississagi Formation; the outlined field in Figure 37 for this formation is based on previously published data and geochemical analyses done as a part of this study. Two samples (rme-3040, rme-0122) (Table 6), which were mapped as a white-mica schist (Figure 6), fall within this same field. Major and REE geochemistry for these two samples show close similarity to rocks of the Mississagi Formation (Table 6, Figure 37). This correlation is supported by that of Lumbers (1973). The field for pelitic schist and gneisses in Figure 37 indicates an intermediate, Fe-enriched composition, which suggests mixed felsic as well as mafic sources for these rocks.

Numerous studies have shown that the REE are a useful indicator of provenance in sedimentary and metasedimentary rocks, particularly in pelitic and semipelitic rocks (e.g., Taylor and McClennan 1985). Further, a large body of REE data exists for the Huronian Supergroup (e.g., McClennan et al. 1979). Consequently, this section focusses on the REE content of the metasedimentary rocks and paragneisses for the Timmins Creek area, particularly those from the Transitional Zone and the Grenville Province.

Figure 38 illustrates normalized to chondrite PASS (Post-Archean average Australian sedimentary rock), NASC (North American shale composite) and ES (European shale) compared to samples from the Timmins Creek area. A strong correlation between these standards and the samples from the study area with respect to LREE and slight diversion in HREE (Figure 38) suggests that the samples from the Timmins Creek area are truly sedimentary in origin. Slightly lower HREE in the Timmins Creek metasedimentary rocks may slightly reflect different Archean source region from the Sudbury area.

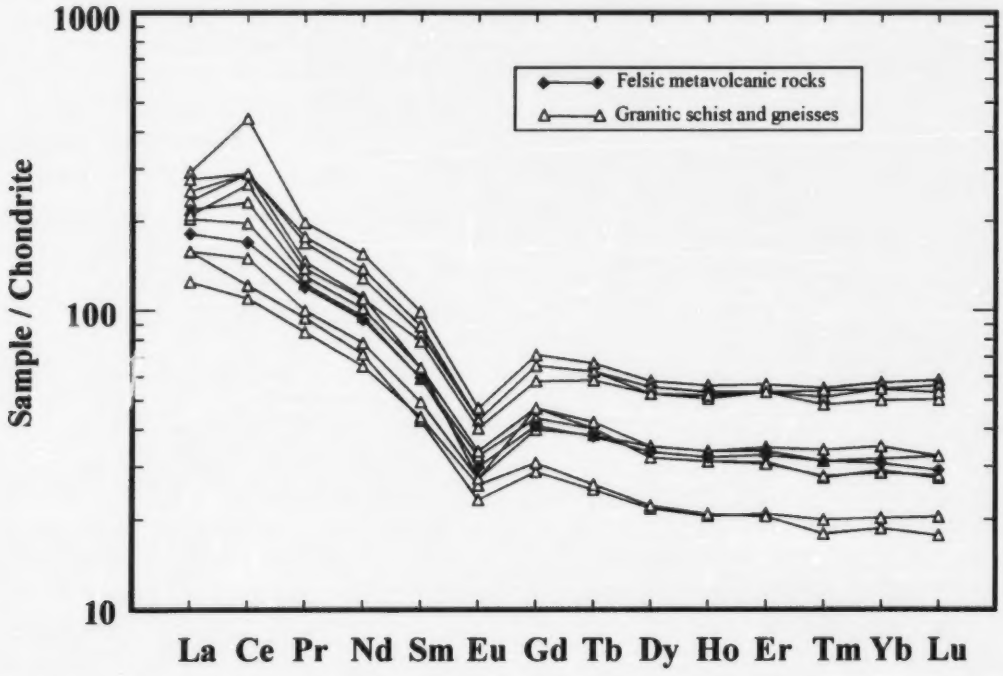


Figure 36. REE patterns for felsic extrusive and intrusive rocks from the Timmins Creek area and Street Township.

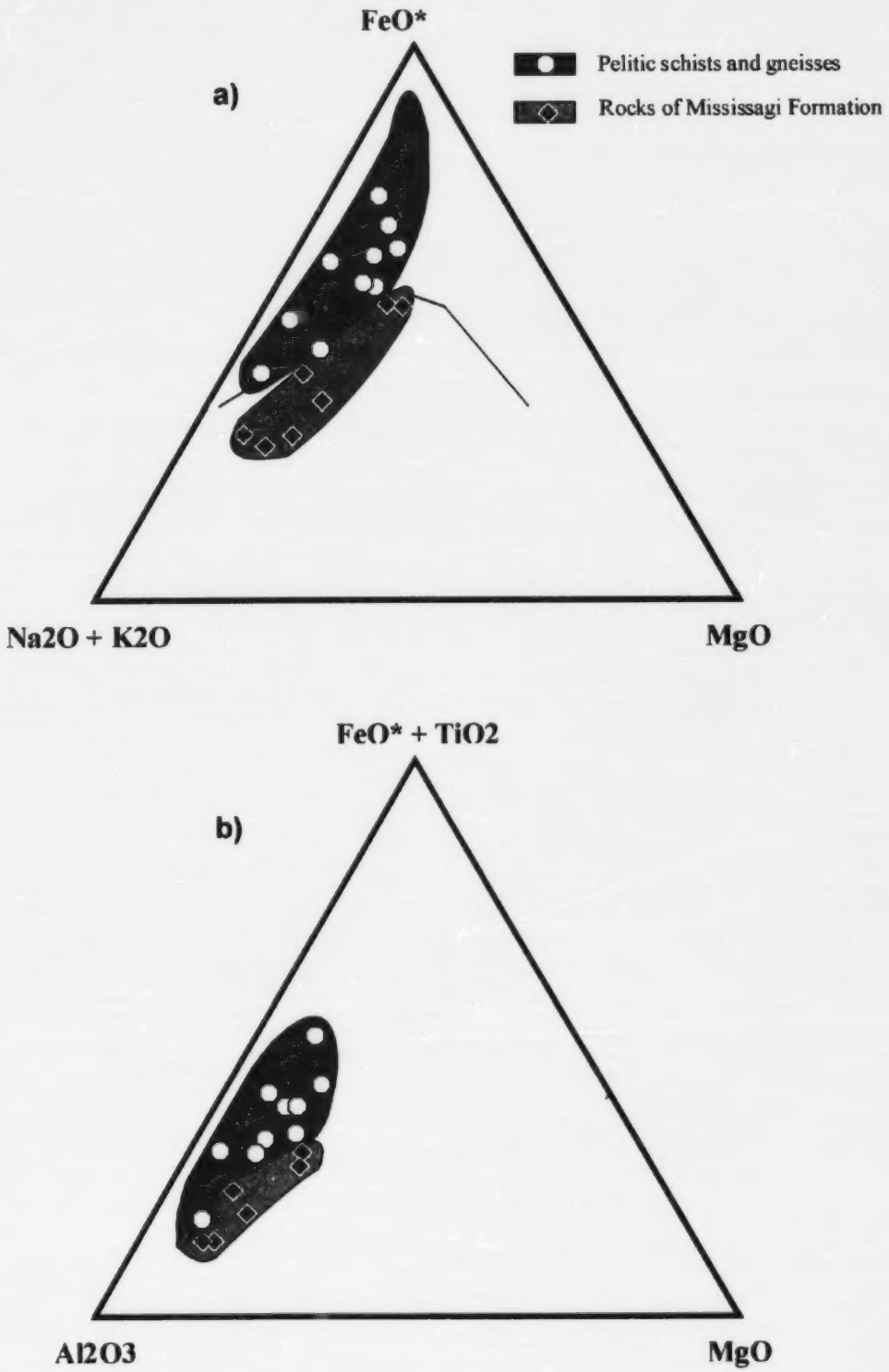


Figure 37. Chemical variation of sedimentary rocks from the Timmins Creek area and Street Township on the diagrams of a) Irvine and Baragar (1971), and b) Jensen (1976).

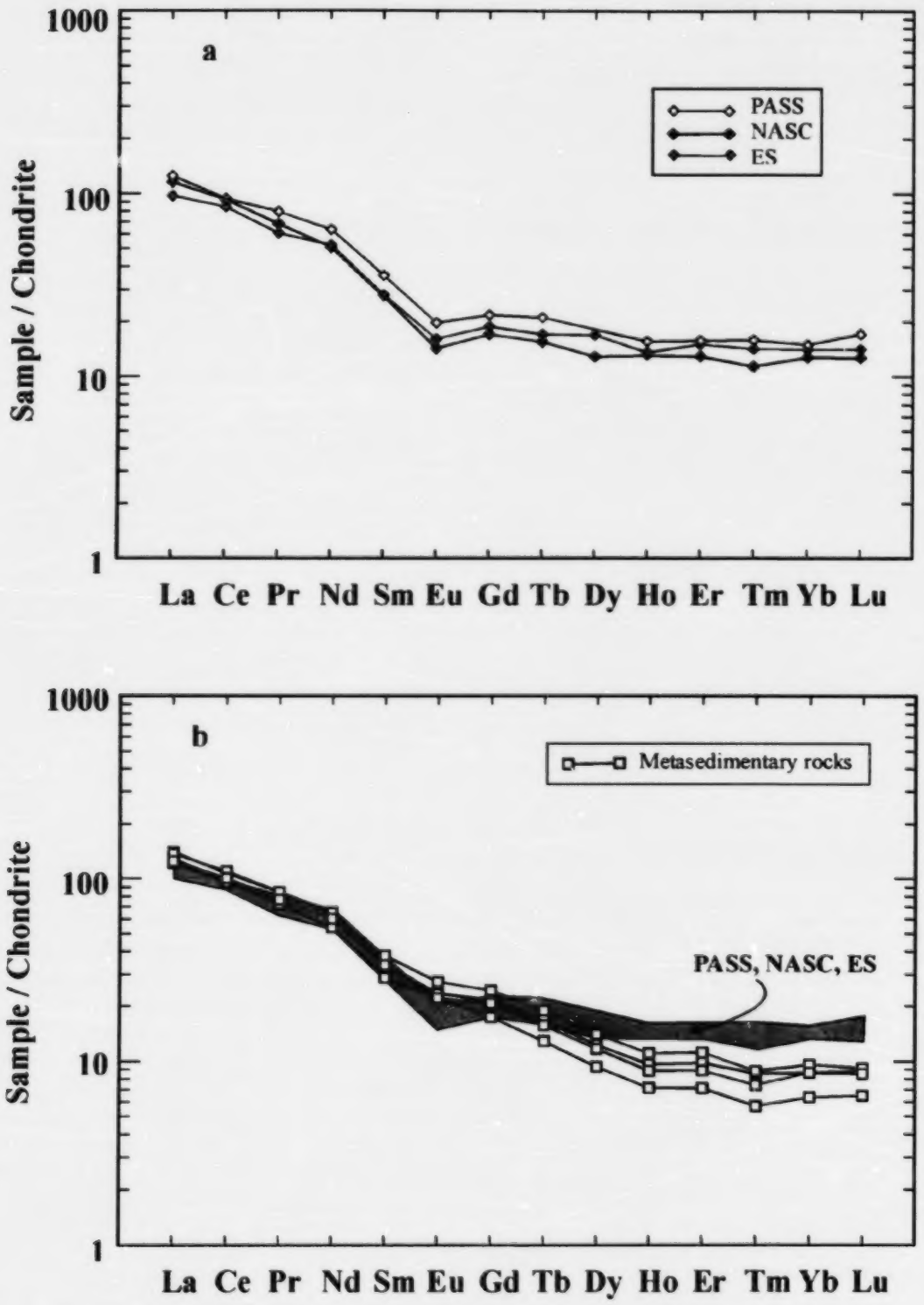


Figure 38. REE patterns for a) PASS (post-Archean average Australian sedimentary rock), NASC (North American shale composite), and ES (European shale); and b) metasedimentary schists and gneisses from the Timmins Creek area.

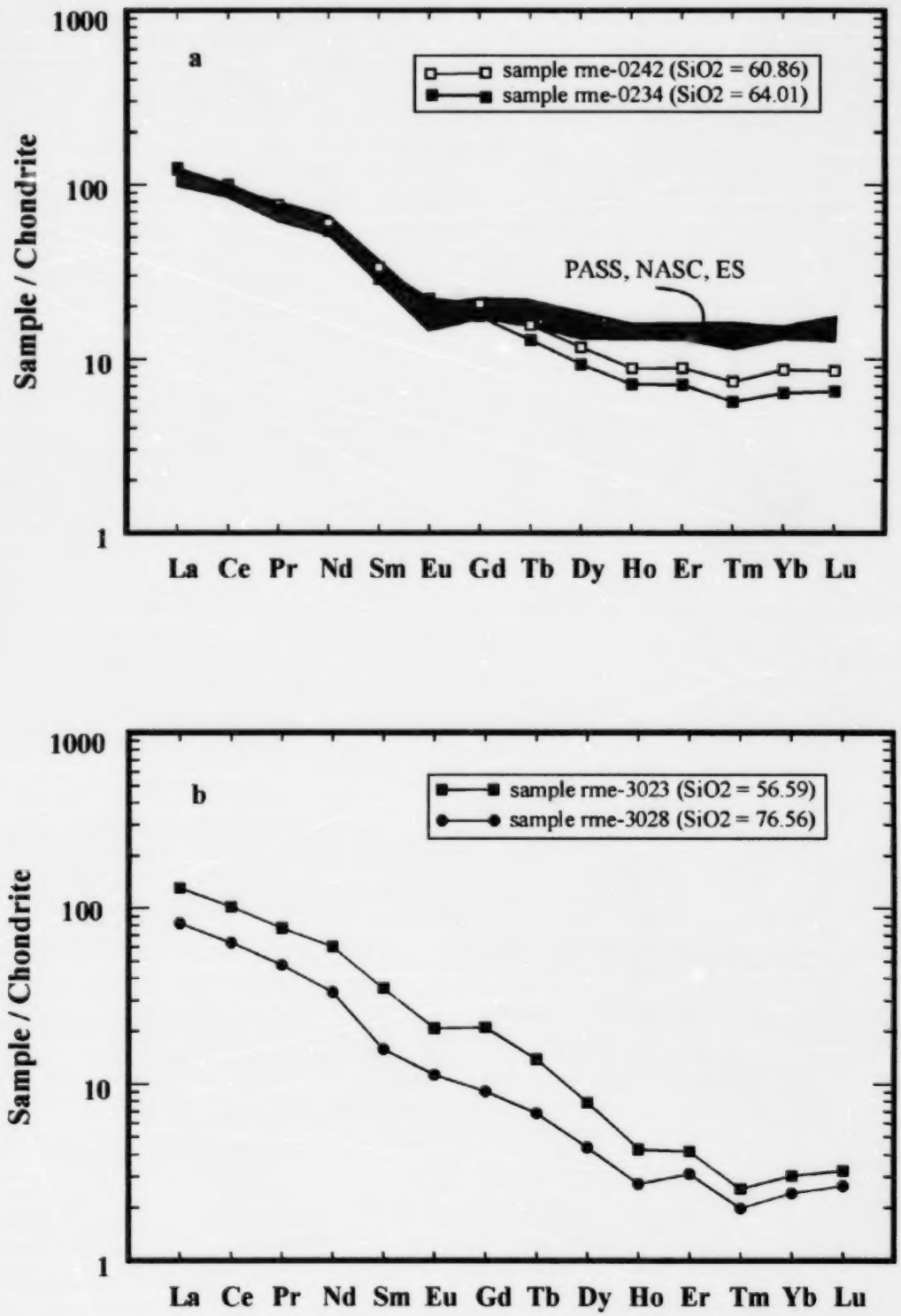


Figure 39. REE patterns for metapelites from the Transitional Zone and the Grenville Province. a) Kyanite-staurolite-bearing schist and gneiss, and b) muscovite-bearing gneisses.

The REE data for Timmins Creek pelitic schists and gneisses are presented in Figures 38 and 39. Their REE patterns have a moderate slope ($La/Yb = 16 \pm 2$) and weak negative Eu anomaly ($Eu/Eu^* = 0.87$). Based on REE patterns, there are no features that can be used to distinguish between metapelites from the Transitional Zone and the Grenville Province (Figure 6). Kyanite-staurolite-bearing schists and gneisses (rme-0242, rme-0234) on both sides of the Grenville Front boundary fault have very similar REE patterns (Figure 39). Strong parallelism in REE patterns is shown by two muscovite-bearing samples (rme-3023, rme-3028) from the south side of the Grenville Front boundary fault indicating that correlation of these rocks is reasonable. The absolute abundance of the $\sum$REE is shown to be a function of silica content (Figure 39). The majority of these pelitic rocks have a typical Huronian REE pattern. Except for the Lorrain Formation, the magnitude of the Eu anomaly is different in an asymmetric way for each metasedimentary formation in the Huronian Supergroup (McClennan et al. 1979). The magnitude of the negative Eu anomaly increases from the base to the top of Huronian stratigraphy (McClennan et al. 1979). The value of the Eu anomaly can be used to correlate specific Huronian Supergroup formations with Timmins Creek rock units. The total REE and value for the Eu/Eu^* indicates that these rocks may be correlated with McKim ($Eu/Eu^* = 0.86 +/- 0.02$), Pecors ($Eu/Eu^* = 0.85 +/- 0.08$) and probably Mississagi formations of the Huronian Supergroup. Major element chemistry essentially eliminate rocks of the McKim Formation (e.g., elements such as Fe). This fact is limited the choice to the Mississagi and the Pecors formations, which, in turn, have different REE patterns. On the binary diagrams $Na_2O + K_2O$ versus SiO_2 and TiO_2 versus Al_2O_3, a majority of the pelitic schists and gneisses from the Timmins Creek area plot in the Pecors Formation field (Figure 40). These rocks also show similar REE pattern to reported Pecors samples (Figure 41a). These data, taken together, illustrate that the metasedimentary rocks within the Transitional Zone and the Grenville Province in the Timmins Creek area are most likely remnants of the Pecors Formation.

There are two samples with distinctive REE patterns (rme-3030, rme-3031) (Figure 41b). Both of these samples have a sharp positive Eu anomaly $Eu/Eu^* = 2.01$, steep LREE depletion and slight HREE enrichment. Similar patterns have been recognized by C.M. Fedo (R.M. Easton, Ontario Geological Survey, personal communication, 1998) from some units within the Mississagi Formation, and are present in some samples collected by Debicki (1990). These unusual patterns may reflect significant input from high-grade Archean gneisses (e.g., the Levak gneisses, located in the north side of the Sudbury Igneous Complex). To date, these unusual patterns have only been found in rocks of the Mississagi Formation, which is consistent with the other results discussed above, indicating that the Timmins Creek metasedimentary rocks are most likely the equivalent of the Pecors and Mississagi formations.

GEOCHRONOLOGY

In conjunction with the mapping project, five geologic units were sampled within Street Township for U/Pb geochronology, with three samples being obtained directly from the thesis area. Some of the results of this study have been alluded to earlier in the thesis. As descriptions and interpretation of the geochronologic data are provided in detail by Corfu and Easton (in press), they are not repeated herein. Instead, for reference, Table 7 summarizes the results from a variety of mineral phases from the samples directly relevant to this study. The significance of these results with respect to the study is examined in the next section.

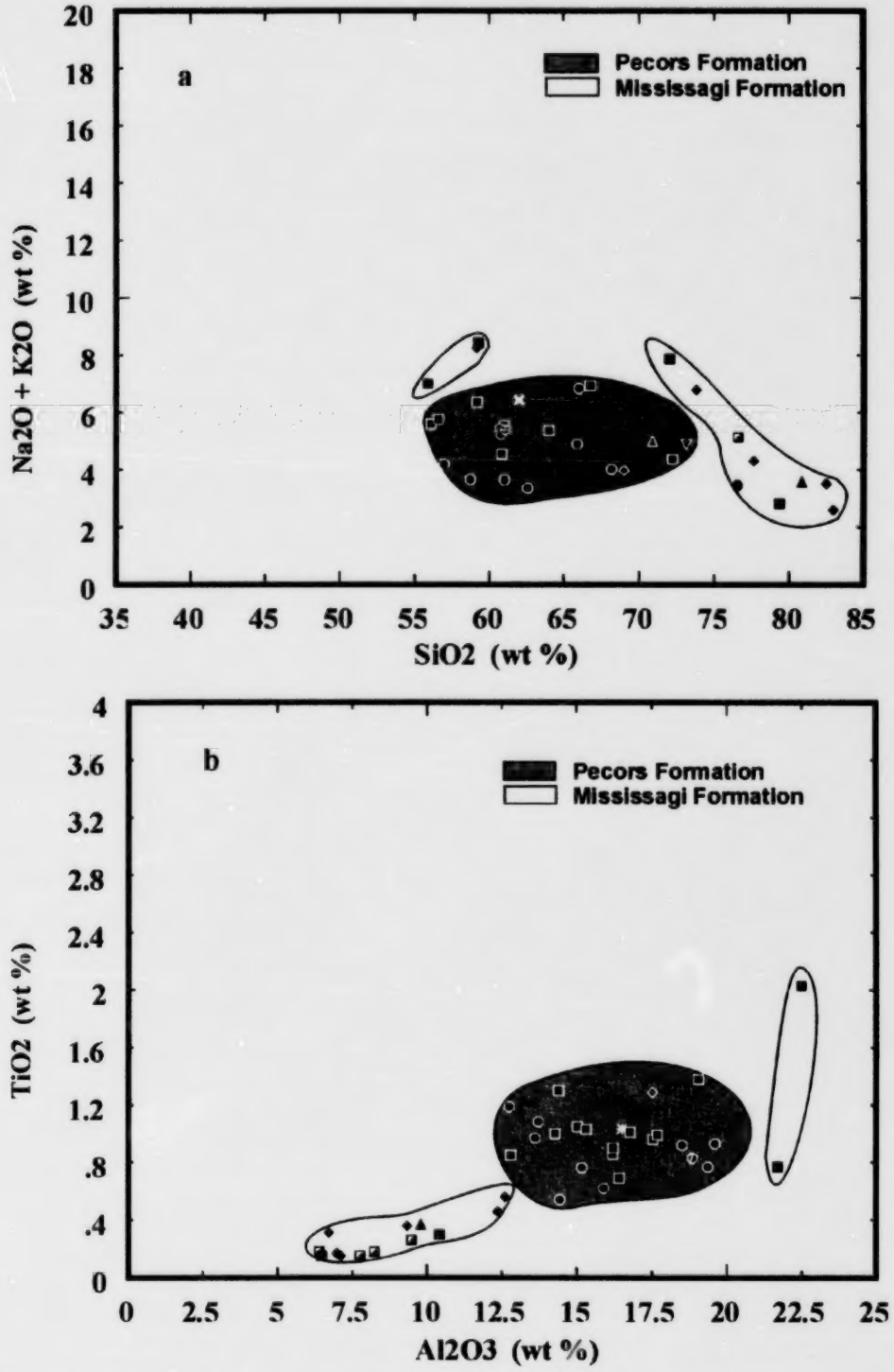


Figure 40. $Na_2O + K_2O$ versus SiO_2 and TiO_2 versus Al_2O_3 diagrams illustrating the chemical variation within the Pecors and Mississagi formations, including samples of schists and gneisses from the Timmins Creek area. The two fields for the Mississagi Formation represent pelites (low SiO_2, high Al_2O_3) and sandstones (high SiO_2, low Al_2O_3).

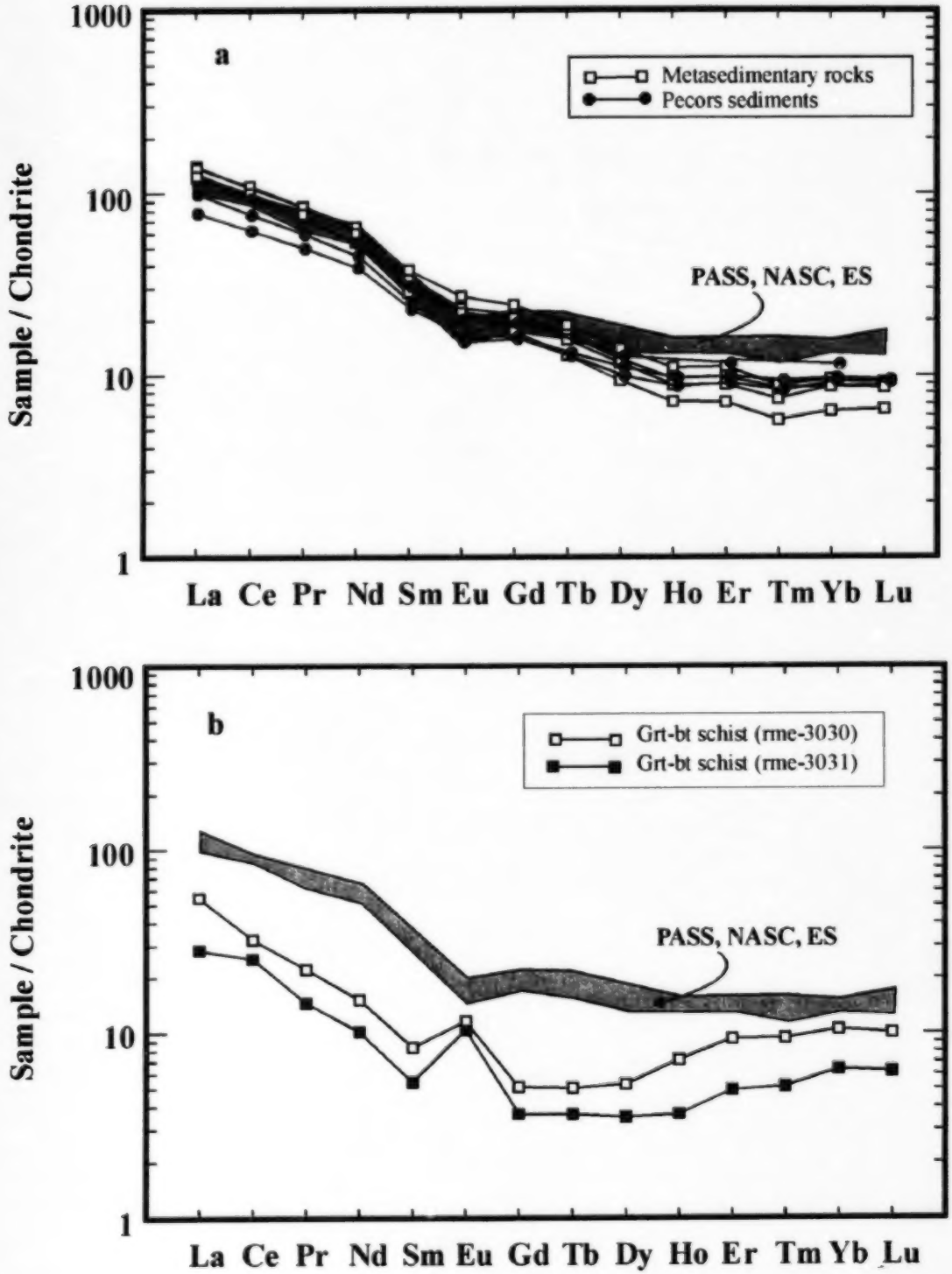


Figure 41. REE patterns for a) Pecors Formation sediments and some metasedimentary rocks from the Timmins Creek area; and b) garnet-biotite schists from the Transitional Zone in the Timmins Creek area.

Table 7. Summary of U/Pb geochronology results from Street Township (data *from* Corfu and Easton, in press).

Sample number and rock type	Older zircon population	Metamorphic zircon and/or titanite	Grenvillian metamorphic zircon	Grenvillian titanite	Grenvillian monazite	Grenvillian rutile	Grenvillian apatite
C-96-5 paragneiss = sample 96RME-242 8.1 kbar, 685°C (S of GFBF)	Archean detrital grains	Discordant metamorphic zircon ca. 1720 Ma	Nearly concordant 992±8 Ma*		Conordant 989±4 Ma*, best estimate of age of metamorphism	Slightly discordant 973±4 Ma*	959±12 Ma+
C-96-6 schist = sample 96RME-3112 7.4 kbar, 665°C (N of GFBF)	Archean detrital grains				987±3 Ma* 982±1 Ma^, best estimate of age of metamorphism	974±4* Ma	949±10 Ma+
C-96-7 granite (N of GFBF) 96RME-3008	2460±20 Ma, upper intercept, best estimate of emplacement age	Upper intercept, 1720 Ma metamorphic titanite					
C-96-3, migmatitic granite gneiss (S of GFBF), (same unit as C-96-7)	2475+25/–10 Ma, upper intercept, best estimate of emplacement age	1720+36/–19 Ma, metamorphic titanite, upper intercept	Concordant 987±9 Ma*	Lower intercept, 977±8 Ma			932±6 Ma+
C-96-2, leucosome in migmatitic granitic gneiss, same outcrop as C-96-3			Concordant, 995±3 Ma*, best estimate of emplacement age (possible inheritance) 987±3 Ma^	987±9 Ma*	Concordant zircon, 995±3 Ma*, best estimate of emplacement age (possible inheritance) 987±3 Ma*,^		
C-96-1, late pegmatite cutting migmatitic granitic gneiss, same outcrop as C-96-3			989±2 Ma*, best estimate of emplacement age	983±5 Ma*, pale titanite			

Symbols: *, oldest $^{206}Pb/^{207}Pb$ age; ^, average $^{206}Pb/^{207}Pb$ ages; +, $^{206}Pb/^{238}U$ age.
Abbreviation: GFBF, Grenville Front boundary fault of Lumbers (1973).

Discussion

STRATIGRAPHIC CORRELATION BETWEEN ROCKS OF THE SOUTHERN PROVINCE AND GRENVILLE FRONT TECTONIC ZONE

As a result of this study (stratigraphic, petrographic, geochemical), it seems quite reasonable to make the stratigraphic correlations shown in Figure 42 between specific formations of the Huronian Supergroup (Southern Province) and the units mapped in the Transitional Zone of the Timmins Creek area. The base of the stratigraphic column (located in the Transitional Zone) in the study area is marked by mafic and felsic metavolcanic rocks and interbedded metasedimentary rocks. These rocks are correlative with similar rock types present in the Stobie Formation in the Southern Province in the immediate vicinity of the Sudbury area. In the Timmins Creek area, these metavolcanic rock units are overlain by polymictic conglomeratic schists that are correlated with the Ramsey Lake conglomerate in Figure 42. This correlation suggests that the upper sedimentary section of the Elliot Lake Group is missing in the Transitional Zone. This is consistent with the aforementioned observations of Dressler (1982) and Debicki (1990). Garnet-biotite schist and staurolite-garnet-muscovite schists (Figure 6) form the remaining portion of the southeast-facing stratigraphy in the Timmins Creek area. In the Figure 42, these two units are correlated with Pecors and Mississagi formations of the Huronian Supergroup, based on the geochemical results previously discussed.

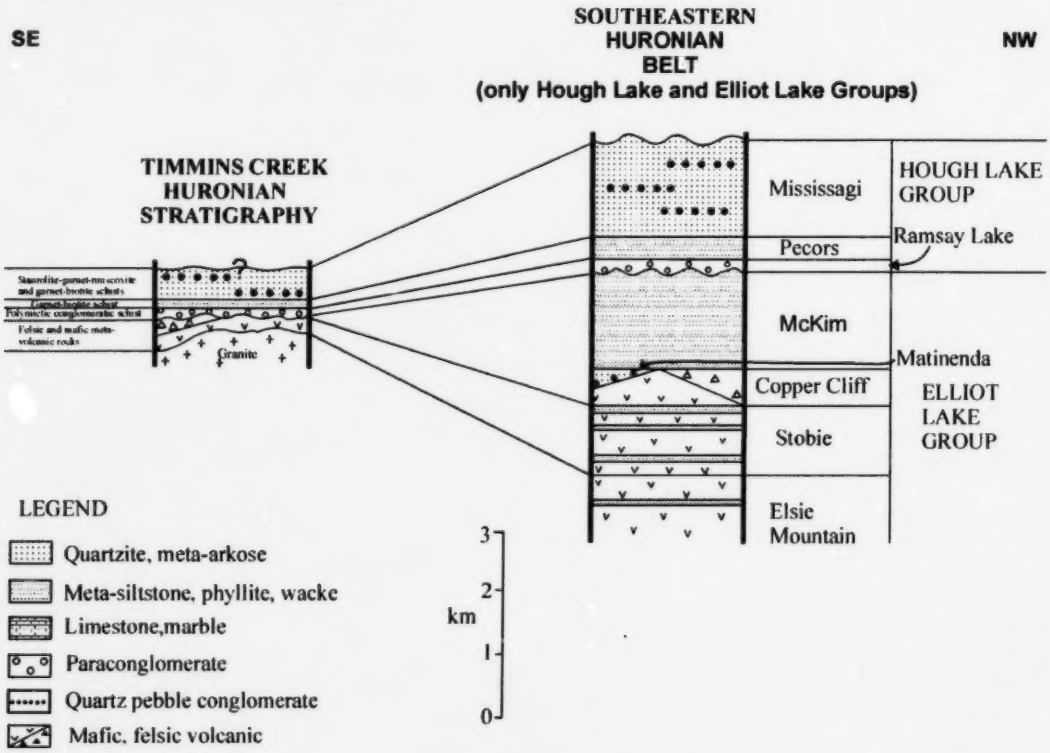


Figure 42. Comparative stratigraphic columns for the Huronian Supergroup from the Sudbury–Elliot Lake area and the Transitional Zone in the Timmins Creek area.

Two types of intrusive rocks occur in the Transitional Zone. The large, thick, sill-like zones of mafic amphibolite (Figure 6) are correlated with the Nippising gabbro suite. The extensive zones of granite in the Timmins Creek area (Figure 6) have been dated at 2460 ± 20 Ma (Corfu and Easton, in press) and probably represent an intrusive phase coeval with Stobie Formation volcanism.

		Maclennan	Scadding	Davis
	Garson	Falconbridge	**Street**	Loughrin
McKim / Sudbury	Neelon	Dryden	Awrey	Hagar

The correlations suggested in Figure 42 are consistent with previous knowledge of the distribution of lower Huronian Supergroup rocks in the Sudbury area (e.g., Card et al. 1977; Debicki 1990; Dressler 1982). For example, rocks of the Stobie Formation are mostly present west of Street Township, where they form an east- to northeast-trending belt in McKim, Garson and southern Falconbridge townships, and a north-trending belt in northern Falconbridge and Maclennan townships (Debicki 1990). The mafic and felsic metavolcanic rocks in the northeastern part of Street Township are believed to be part of the same volcanic belt and appear to be part of a major mafic to felsic volcanic cycle, that grades upward from mafic flows to felsic flows and pyroclastic rocks. This correlation is supported by the geochemical data, which uses major and trace elements to illustrate that the metavolcanic rocks in the Timmins Creek area are correlative with lower Huronian volcanic rocks of Stobie Formation. The geochemistry of the felsic metavolcanic rocks and granites (U/Pb age of 2460 ± 20 Ma) from the Timmins Creek area are not similar to the Copper Cliff felsic volcanic rocks and Creigton and Murray granites. If these correlations are valid, then the metavolcanic rocks in the Timmins Creek area are the easternmost extension of metavolcanic rocks of the Stobie Formation in the Sudbury region.

Rocks of the McKim Formation in the Southern Province form a northeast-trending belt from McKim Township across Neelon, Garson and part of Falconbridge townships. In McKim Township, this formation is about 1300 m thick and it thins toward the east in Neelon and Garson townships and is absent in Falconbridge Township. This thinning of the formation eastward is consistent with its absence in the Timmins Creek area. In addition, whole rock geochemistry of pelitic schists in the Transitional Zone, Timmins Creek area, shows significant differences between the rocks which were studied and the McKim Formation. These data support the interpretation in Figure 42 that the McKim Formation is absent in the Transitional Zone of the Timmins Creek area.

There is no reliable evidence of a protolith for the conglomeratic unit in the Transitional Zone, which is exposed immediately southeast of the mafic metavolcanic unit in Street Township. Tentatively, these rocks are assigned to the Ramsey Lake Formation, because they have a gradual and conformable contact with the overlying garnet-biotite schists (interpreted to be the Pecors Formation). This relationship is analogous to that observed in Falconbridge Township were the Ramsay Lake Formation overlies the Stobie Formation (although the contact between the Ramsay Lake and Stobie formations is not exposed) (Debicki 1990). It is also consistent with the results of this study suggesting the absence of the Matinenda and McKim formations in the study area.

In the Southern Province, south and southwest of Wanapitei Lake, rocks of the Pecors Formation occur as discontinuous patches. In McKim, Neelon, Garson and Falconbridge townships (Southern Province), the Pecors Formation overlies the Ramsay Lake Formation. Characteristics of the contact between these two formations are given in the literature (Debicki 1990) and are similar to those which are described for the metaconglomerate and garnet-biotite schists in the Timmins Creek area. In Maclennan Township (Southern Province), the Pecors Formation overlies the Matinenda Formation; the contact is abrupt, but conformable. This indicates the possibility of the presence of Matinenda Formation conglomerate in the Timmins Creek area. Major and trace element geochemistry data obtained for the garnet-biotite schists from the Timmins Creek area show strong similarities with the Pecors Formation, and support the correlation shown in Figure 42.

In Street Township, rocks of Mississagi Formation within the Southern Province occur as massive, homogenous quartzite with interbeds of sheared, silty varieties. These types of Mississagi quartzites may represent the protolith of garnet-biotite and garnet-staurolite-muscovite schists in the southwestern part of the Transitional Zone, in the Timmins Creek area (Figure 6). This is supported by whole rock and REE geochemistry data. In the study area, the lower contact of the garnet-biotite schist (Mississagi Formation) is not exposed, but stratigraphic data in neighbouring southern Falconbridge Township shows that the Mississagi Formation overlies the Pecors Formation.

The identification of the lithological protolith of gneisses of the Grenville Province is much more problematic. These rocks have been metamorphosed to higher grade and formed leucosome material as a result of partial melting. Whole rock geochemistry, including REEs and mineral geochemistry suggest that some rock units south of the Grenville Front boundary fault (Lumbers 1973) in the Grenville Province are very similar to those which occur in the Transitional Zone, and, thus, may be correlative with the Huronian Supergroup.

POSITION OF THE GRENVILLE FRONT

In the Timmins Creek area, the Grenville Front boundary fault separates rocks of the Transitional Zone from those of the Grenville Province. The following distinctive features set apart these two groups of rocks:

Transitional Zone
- relics of primary structures and textures are present in schists;
- clear distinction of S_0 and S_1 fabrics and F_1 folds are presented;
- no evidence of melting is shown in mineralogy of metapelites.

Grenville Province (in the Timmins Creek area)
- high-grade gneissic rocks; questionable recognition of S_0 is typical, although at some localities S_0 is clearly observed;
- migmatites and conformable pegmatite zones are common;
- refolding of F_1 folds, but no S_2 fabric is observed;

Field observations record no evidence of significant vertical or horizontal movement along the Grenville Front boundary fault . The Grenville Front boundary fault is really a "migmatization front". In the *P–T* space of the Carmichael diagram (Figure 23), this boundary lies on or above the melting curve for metapelites, which is in general agreement with the *P–T* estimates for the metapelite assemblages, which come from either side of the Grenville Front boundary fault in the study area. This position in the *P–T* space would fully explain the abrupt disappearance of migmatitic material north of the Grenville Front boundary fault. Structurally, the Grenville Front boundary fault is a brittle-ductile boundary between the Transitional Zone and Grenville Province. This is probably related in age to the Grenville

Front (post-F_2 deformation, metamorphism) and defines the northwest limit of penetration by second-generation pegmatites. As a result, the most significant differences between rocks of these two domains are 1) the degree of metamorphism, which progressively increases southward from the Grenville Front (Ess Creek fault), 2) the development of leucosome material within the rocks in the Grenville Province, and 3) the preservation of different structural events.

Is the Grenville Front boundary fault in the Timmins Creek area truly the boundary between the Grenville and Southern geological provinces? Studies of the structure, petrography, metamorphism and geochronology in this area suggest that this boundary coincides with the Ess Creek fault, rather than the Grenville Front boundary fault. This means that the position of the Grenville Front is 1 to 1.5 km further north than previously indicated, in a 25 km long zone from the Timmins Creek area east to River Valley (Figure 1). The data obtained show several points.

1. Fold patterns in the Grenville Province and Transitional Zone are similar and distinct from those in the Southern Province.
2. Mineral chemistry and whole rock geochemistry indicate that rocks in the Transitional Zone and Grenville Province have a similar origin and metamorphic history.
3. Thermobarometry using a variety of individual calibrations, as well as TWEEQU and INVEQ, using staurolite-kyanite-garnet-biotite-muscovite bearing assemblages, indicate conditions of 7 to 8 kbar and 630 to 680°C in the Transitional Zone, and 8 to 9 kbar and 685 to 725°C in the Grenville Province. For the Southern Province, mineral paragenesses indicate T ~350°C; pressure is not well constrained, but is at most ~3 kbar (Bucher et al. 1994).
4. Best estimates of timing of partial melting and closure through 700°C is 995 ± 2 Ma, from a U/Pb zircon age determined from folded leucosome in the Grenville Province (Table 8).

The second stage of deformation is constrained between 995 and 990 Ma, based on U/Pb zircon ages of folded and undeformed leucosome in the Grenville Province. U/Pb age determinations on metamorphic monazite from pelites in both the Grenville Province and Transitional Zone give an age 987 ± 3 Ma and represent closure through 650°C, confirming the suggestion that Grenville Province and Transitional Zone have had similar tectonic histories (Table 8).

COOLING HISTORY OF THE TIMMINS CREEK AREA

The P–T results agree with the geochronological data (Corfu et al. 1998; Corfu and Easton, in press), which indicate that, within 1.5 to 2 km of the Grenville Front, the temperature attained during the Grenvillian orogeny was similar to the closure temperature of zircon (>700°C).

Based on the thermochronological data obtained from the samples in the Timmins Creek area (Table 8), a temperature–time (T–t) history of a sample can be determined. In Figure 43, the U/Pb age data based on zircon and titanite are similar, hence, it can be assumed that the peak metamorphic temperature was near the closure temperature for U/Pb in zircon. This result is supported by geothermometry, where the peak metamorphic conditions are 8.2 kbar and 725°C. The plot shows successively younger ages for titanite, rutile and apatite. The T–t history, defined by these ages, shows rapid cooling (15°C/m.y.) through the temperature interval 700 to 550°C, followed by a period of relatively slow cooling (4.5°C/m.y.) through the temperature interval 550 to 400°C, with the average cooling rate estimated as 5.5°C/m.y.

Haggart et al. (1993) and Krogh (1994) obtained U/Pb thermochronological data from Killarney area for zircon, monazite and titanite, and $^{40}Ar/^{39}Ar$ data for potassium feldspar, muscovite and biotite. These data show a rapid cooling through the temperature interval 650 to 350°C over 25 Ma at a cooling rate of 12°C/m.y., and 5.8°C/m.y. over 60 Ma with temperature change from 650 to 300°C. These results are compatible with those obtained in this study.

Similar results were obtained in detailed metamorphic and geochronological studies of the Grenville Front in the Temagami area (Smith et al. 1994; Krogh 1994; Krogh and Davis 1969). These results are fully compatible with data presented in this study (Table 8). The cooling rate is 7°C/m.y. over a temperature range 650 to 300°C over 50 Ma.

Cooling rates for the Grenville orogenic event were calculated by Mezger et al. (1989) in a study of cooling history of the Adirondack Highlands, New York, USA. These data are based on U/Pb ages of garnet, monzanite, titanite and rutile, and $^{40}Ar/^{39}Ar$ ages from hornblende and biotite. Initial cooling from the inferred peak temperature of 750°C is 4°C/m.y. decreasing to 1°C/m.y. as the terrane cools. Similar slow cooling rates of 2 to 4°C/m.y. were reported for the Grenville Orogen in Ontario by Cosca et. al. (1991). The data of Mezger et al. (1989) and Cosca et al. (1991) represent averages for the entire of the orogen. In contrast, the cooling histories reported here and elsewhere along the Grenville Front reflect cooling histories at the margin of the orogen and, consequently, would be expected to show more rapid cooling, reflecting more rapid uplift and exhumation at the margin of the orogen.

Table 8. Cooling history data along the Grenville Front in the Sudbury area.

Timmins Creek (all data) (Corfu and Easton, in press)

Age	Closure Temperature	Mineral, Method	Comments
995±3 Ma	>700°C	Zircon, U/Pb	C5, C2-C1 zircon range 989 to 995±3 Ma
987±3 Ma	650°C	Monazite, U/Pb	C6 concordant monazite $^{207}Pb/^{206}Pb$ age, C5,C6 monazite range from 989 to 977 Ma
987±9 Ma	550°C	Titanite, U/Pb	C3 concordant $^{207}Pb/^{206}Pb$ age
974±4 Ma	430°C	Rutile, U/Pb	C5, C6, $^{207}Pb/^{206}Pb$, most concordant grains
949±10 Ma	400°C	Apatite, U/Pb	C6, $^{207}Pb/^{238}U$
Cooling 700 to 400°C in 46 Ma = 6.52°C/m.y.			
Cooling 700 to 400°C in 59 Ma = 5.10°C/m.y.			Max. zircon to minimum apatite (slowest cooling)
Cooling 700 to 400°C in 33 Ma = 9.10°C/m.y.			Min zircon to max. apatite (fastest cooling)

Killarney Area (Haggart et al. 1993; Krogh 1994)

Age	Closure Temperature	Mineral, Method	Comments
977±12 Ma	>700°C	Zircon, U/Pb	
988±2 Ma	650°C	Monazite, U/Pb	
978±13 Ma	550°C	Titanite, U/Pb	
975 to 1000 Ma	340°C	Potassium feldspar, Ar/Ar	
930±5 Ma	320°C	Muscovite, Ar/Ar	
970 to 1240 Ma	300°C	Biotite, Ar/Ar, K/Ar	Excess Ar
Cooling 650 to 350°C in 25 Ma = 12.0°C/m.y.			
Cooling 650 to 300°C in 60 Ma = 5.8°C/m.y.			

Temagami Area (Smith et al. 1994; Krogh 1994; Krogh and Davis 1969)

Age	Closure Temperature	Mineral, Method	Comments
988±5 Ma	>700°C	Zircon, U/Pb	
988±5 Ma	650°C	Monazite, U/Pb	
991±2 Ma	550°C	Titanite, U/Pb	
977±4 Ma	500°C	Hornblende, Ar/Ar	
938±4 Ma	320°C	Muscovite, Ar/Ar	
954±4 Ma (max).	300°C	Biotite, Ar/Ar, K/Ar	Excess Ar, other samples range from 1260 to 1008 Ma
940 Ma	300°C	Biotite, Rb/Sr	
842 Ma	?°C	Apatite, Rb/Sr	
Cooling 650 to 300°C in 50 Ma = 7.0°C/m.y.			

Note: m.y., one million years.

P–T–t PATH FOR THE TIMMINS CREEK AREA

There are several techniques to evaluate the *P–T–t* paths followed by rocks during a metamorphic event. These are 1) mineral zoning studies (Spear and Selverstone 1983); 2) calculation of pressure and temperature from retrograde mineral assemblages (Jamieson 1986); 3) order-disorder kinetics (Anovitz et.al. 1988); 4) $^{40}Ar/^{39}Ar$ systematics (Cosca et al. 1987); and 5) geophysical models (England and Thompson 1984; Thompson and England 1984).

Analyses of "core" and "rim" compositions of individual minerals for the purpose of *P–T* estimates were obtained for most samples in this study. "Core and rim" analyses on garnet, biotite, hornblende and plagioclase show the lack of significant zoning in most cases (Murphy 1999). This means that *P–T* data could not be used to generate *P–T–t* paths. However, *P–T* data from different samples can be linked into *P–T–t* paths if the samples share a common metamorphic history, if each sample can be placed in its correct relative position in the metamorphic sequence, and if the samples are spaced closely enough that major differences in *P–T–t* history between outcrops are unlikely (Jamieson et al. 1995). Samples from the Transitional Zone and Grenville Province meet these criteria, and a small section on the proposed *P–T–t* path is illustrated in Figure 44 for the Timmins Creek area, Street Township (Figure 6), using the *P–T* data reported herein.

A scenario of "suddenly doubled crust" was suggested by England and Thompson (1984) to explain the formation of medium- to high-grade metamorphic rocks; this idea has been tested in the Timmins

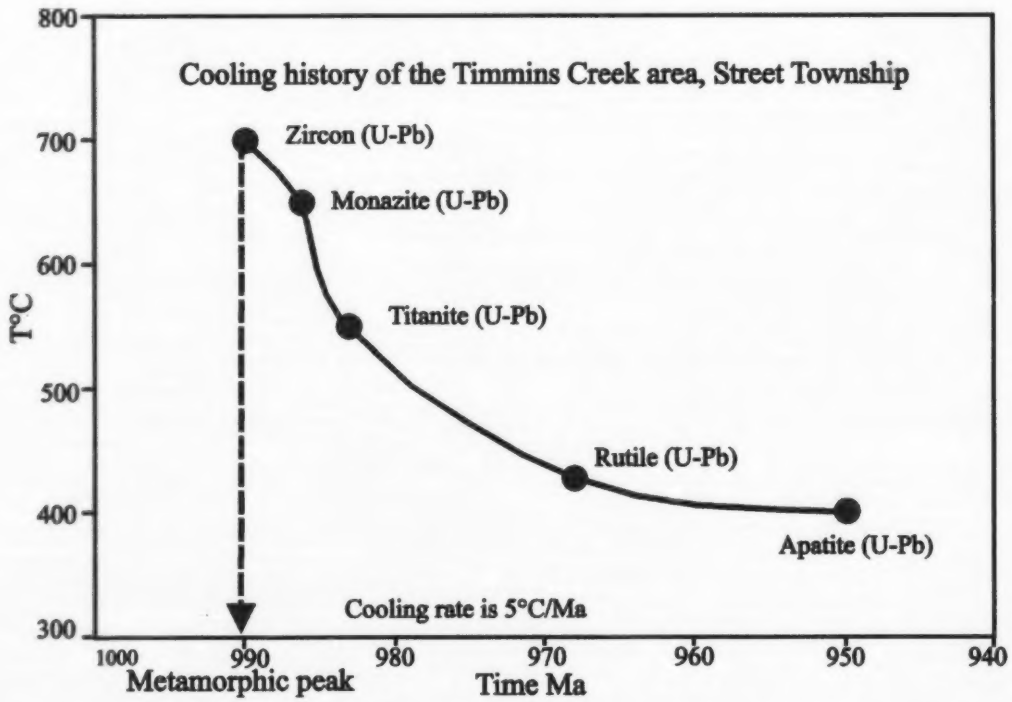


Figure 43. Temperature–time (*T–t*) history curve for the Timmins Creek area, based on work by Corfu et al. (1998), Corfu and Easton (in press), and R.M. Easton (Ontario Geological Survey, written communication, 1998).

Creek area as one of the sections within the western part of the Grenville Front tectonic zone. In Figure 44, loading of crust via thrusting and subsequent isobaric heating to near peak temperatures is suggested as the result of this process, and is followed by a period of uplift and cooling with a monotonic decrease in both pressure and temperature. This results in the clockwise *P–T–t* path that is often suggested in the literature.

Bethune (1993) estimated peak pressures and temperatures in the order of 8 kbar and 680°C for Sudbury metadiabase from the western Grenville Front tectonic zone near Tyson Lake, and determined a *P–T–t* path suggesting near isothermal decompression (680 to 700°C) over the range from 8 to 5 kbar. She described an increase in pressures and temperatures southeast of the Grenville Front. These results are consistent with the data presented above and with the generally accepted interpretation that the southern Grenville Front tectonic zone represents the deeper structural level relative to the northern Grenville Front tectonic zone.

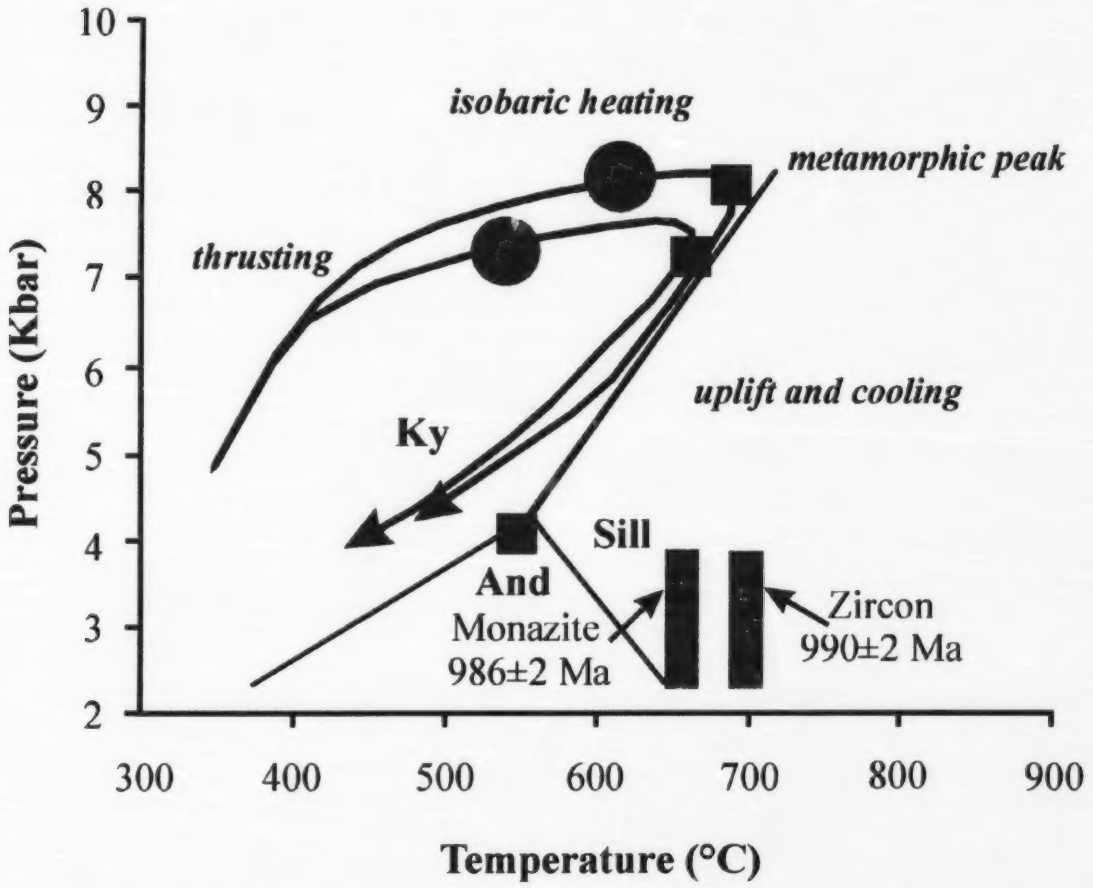


Figure 44. Generalized pressure–temperature–time (*P–T–t*) paths for the Timmins Creek area: a) Transitional Zone, and (b) Grenville Province.

TECTONIC MODELLING FOR THE GRENVILLE FRONT TECTONIC ZONE

Each terrane in the Grenville Orogen has some unique geological features, as well as features in common with other geological domains. This study does not attempt to reconstruct the detailed evolution of the crust during the thrusting event that resulted in the formation of the Grenville Front tectonic zone in the Sudbury region. In general, all plate tectonic processes operate on a time scale that is rapid relative to thermal relaxation. Therefore, large-scale tectonic disturbances, such as overthrusting, occur almost instantaneously, when compared with the time scale for relaxation of the perturbation (Spear 1993).

Recent modelling of the Grenville Front tectonic zone in Ontario, by workers such as Jamieson et al. (1989), Haggart et al. (1993), Rivers et al. (1993), Bethune (1997) and Bethune et al. (1997), have been based heavily on finite-element models of convergent orogens as described by Jamieson et al. (1989), Beaumont et al. (1992) and Willet et al. (1993). These models suggest that continent–continent collision results in specific geometries at the flanks of the orogenic belts. In particular, these models suggest that exhumation of deep-seated rocks accompanies formation of a large hanging-wall antiform, which develops above a crustal-scale, "retro-shear" zone, which separates the hanging wall from the footwall. The retro-shear zone initially develops where subcrustal lithosphere is detached and subducted during collision, but as the orogen grows, the retro-shear migrates into the foreland, driven by crustal thickening in the interior of the orogen. These models have been useful in explaining many features of the Grenville Front tectonic zone, such as the exhumation of high-pressure (~14 kbar) rocks along the southern edge of the Grenville Front tectonic zone and the rapid cooling history. They have been less effective, however, in explaining much of the detailed geologic history recorded along the Grenville Front itself.

The tectonic model presented herein attempts to integrate the general elements of the finite-element models with the geologic relationships observed by the author in the Timmins Creek area. Figure 45 illustrates, in a simplified drawing, the aforementioned overthrusting models. In Figure 45, points a, b and c represent localities which are subsequently exposed on surface within the Southern Province, the Transitional Zone and the Grenville Province in the study area, respectively. In Figure 45a, northwest–southeast compression of stable strata is implied to have occurred south of the current Grenville Front tectonic zone, causing early penetrative shortening of rocks within the Southern Province, and accompanied by overthrusting of deeper level transported rocks from the southeast (Figure 45b). This led to burial and metamorphism of the rocks within the Transitional Zone and the Grenville Province (b and c, respectively, in Figure 45b). A period of thermal relaxation in the rocks of these two domains must have followed, allowing medium to high metamorphic assemblages to be formed with simultaneous development of southwest–northeast-striking foliation and migmatites. The latter formed as a result of metamorphic reactions causing dehydration of the buried sediments, which ultimately led to partial melting. Later deformation led to further shortening, initiation of uplift, development of folds and accumulation of additional strain in the rocks (Figure 45c). During this stage, the rocks of the Transitional Zone and the Grenville Province continued to be uplifted to higher crustal levels, resulting in the formation of the antiform structure. Late microstructures and brittle-ductile faults (such as the Grenville Front boundary fault) formed at the same time as the pegmatite system that crosscuts previously folded migmatitic rocks. Some late movement on both the Ess Creek fault and the Grenville Front boundary fault may have occurred as the exhumed rocks in the study area were cooling.

The conditions of metamorphism in the Transitional Zone suggest that rocks closer to the Grenville Front were never buried as deeply as those farther southeast in the Grenville Province. The peak metamorphic conditions recorded in this study suggest that the Grenville Province samples were metamorphosed at crustal depths of greater than 25 km (~7 to 9 kbar) and temperatures of greater than

700°C. It is assumed that the mechanism of heating of rocks in the Timmins Creek area was relatively quick, since no older metamorphic history was observed in the rocks, and there was no evidence of a multi-stage growth history in the metamorphic minerals dated by Corfu and Easton (in press). Therefore, timing of the overthrusting event depicted in Figure 45 was relatively rapid, that is, between 995 and 990 Ma as indicated by leucosome and pegmatite data. In addition, rapid heating (roughly 5 Ma) may have been accentuated if the transported rocks were initially hot, that is, exhumed from depth as the "retro-shear" model would predict. The rate of heating at the early stage of orogeny is not known.

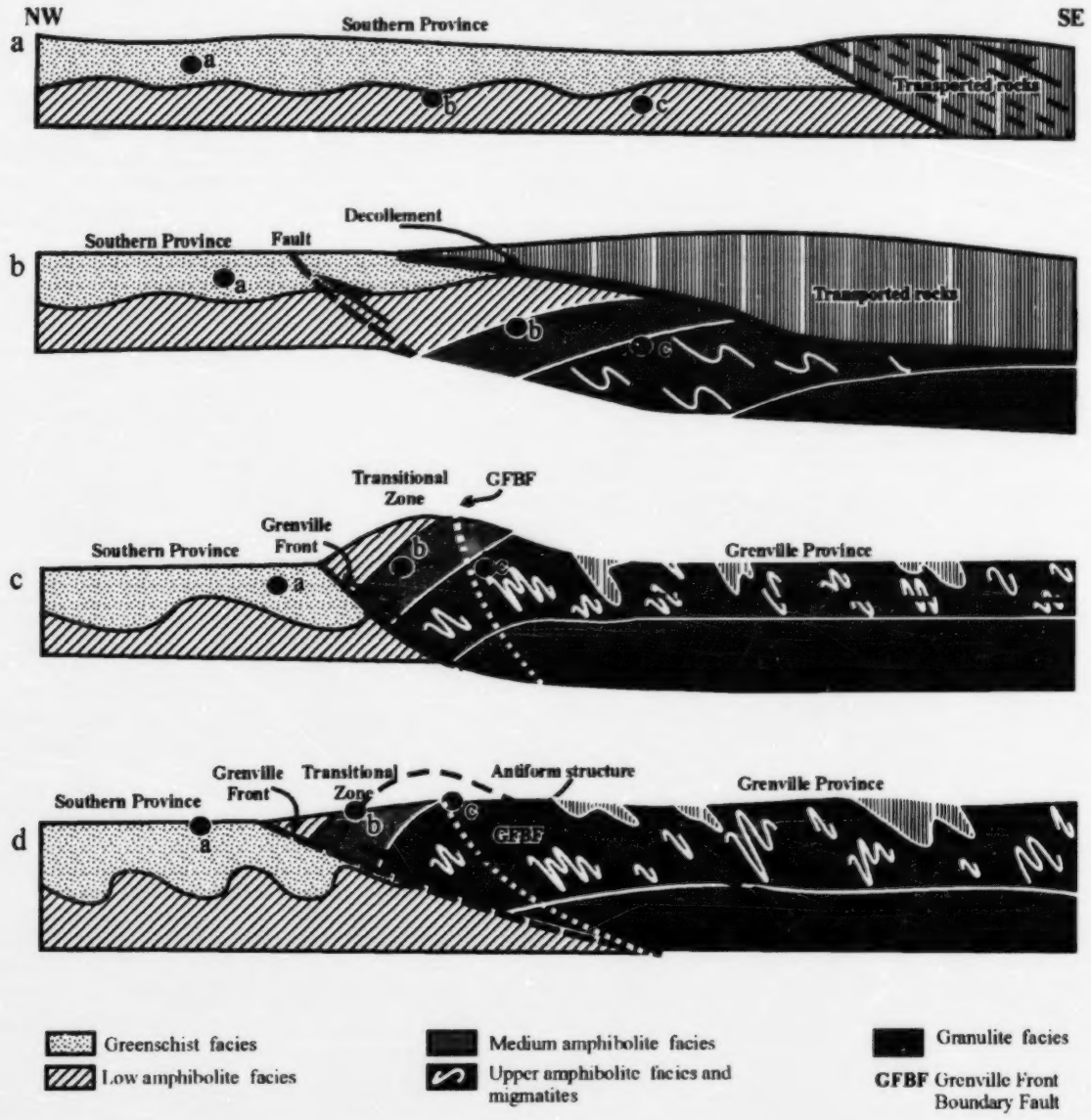


Figure 45. Tectonic model for the Timmins Creek area based on tectonic thickening due to overthrusting. Points a, b and c represent localities in the Southern Province, the Transitional Zone, and the Grenville Province, respectively.

The present tectonic model allows one to speculate how to interpret aspects of the geology and metamorphism of Street Township. The antiform structure shown in Figures 45c and 45d is the secondary fold in the north-northwest limb of the hanging-wall antiform structure, which finite-element modelling predicts should exist along the northwest margin of the Grenville Front boundary fault. Therefore, the synform in Domain 2 (Easton and Murphy, in press.) (Figure 5) could represent a complimentary structure immediately north of the hanging-wall antiform. Further, there are no observations of Sudbury dikes south of Domain 2 in Street Township (i.e., in Domain 3 rocks). This fact can be explained if the intrusion of these dikes occurred prior to the thrusting event, or if the transported rocks are allochthonous with respect to the Southern and Superior provinces. Orthopyroxene hornblendite pods associated with migmatitic quartzofeldspathic gneisses of Domain 3 (Figure 5), which wrap around dominantly non-migmatitic rocks of Domain 4, are probably tectonic slivers of the transported rocks (Figures 45c and 45d). The formation of the leucosome material in the Domain 3 migmatitic gneisses could be explained by the amount of fluid trapped in the system by the overthrusting of hot transported rocks on the relatively wet sediments of the Southern Province. The enclaves represented by Domain 4 may represent a regional reflection of the hanging-wall antiform, which brings up underlying lower plate rocks. If so, then the initial thrust boundary was folded after emplacement, which is consistent with the proposed model (Figures 45c and 45d).

On the regional scale, the tectonic model can explain some differences in the metamorphic grade across the Grenville Front, from Killarney out to Labrador. Cross-sections of the western margin of the Grenville Province in the Killarney and the Timmins Creek areas and Labrador represent an exposure of different structural levels. All of them show an abrupt metamorphic transition from pre-Grenvillian greenschist facies assemblages in the foreland of the Southern and the Superior provinces and higher grade metamorphic rocks of the Grenville Province. In the Killarney area, the metamorphic grade, immediately southeast from the Grenville Front, ranges from upper amphibolite to granulite facies assemblages (Bethune et al. 1988), which represents a deeper crustal level. The great lateral extent of Sudbury diabase dikes into the Grenville Front tectonic zone in the Killarney area is also consistent with exposure of a deeper crustal level of the Southern Province. In the Timmins Creek area, metamorphic grade south-southeast of the Grenville Front increases from middle to upper amphibolite facies assemblages, which correspond to mid-level crust. The presence of rocks of the possible overthrust sheet (i.e., Domain 3) also suggests a somewhat higher level of exposure than at Killarney. Finally, in western Labrador, metamorphic grade in the fold-and-thrust belt varies from greenschist facies near the Grenville Front to upper amphibolite facies about 30 km to the southeast (Rivers 1993). In this case, an exhumation of upper level crust occurs in this area in the vicinity of the Grenville Front.

To summarize the discussion about the proposed tectonic model, some specific features of it should be mentioned. Although this model is largely based on the Jamieson et al. (1989) type model, it differs from it in several critical ways. 1) Many previous workers have assumed that the "retro-shear" zone corresponds with the Grenville Front (e.g., Jamieson et al. 1989). In the proposed model, the active part of the "retro-shear" zone lies inboard within the Grenville Front tectonic zone. And, in all probability, the Grenville Front represents a "last gasp" of a migrating "retro-shear" zone into its foreland. In the waning stage of the Grenville orogeny, the "retro-shear" is coincident with the Ess Creek fault, an eastern continuation of the Wanapitei–Murray fault system. The presence of an earlier major fault (Ess Creek fault) may have served to localize the "retro-shear", namely, the Grenville Front, here. 2) The consequence of the model depicted in Figure 45, and based on all the observations within the body of the thesis, is that there is no need to invoke extreme exhumation in the area of the Grenville Front. This allows for continuity of strata (Huronian, Sudbury dikes, presence of 1700 Ma metamorphic event in the Timmins Creek area, which is preset just north of the Ess Creek fault in Scadding and Davis townships) across the Timmins Creek area without the need for considerable uplift. This is consistent with *P–T* data and metamorphic history from the Timmins Creek area. It may also provide a mechanism for dilemma

that Smith et al. (1994) faced: namely, that the asymmetry of the excess Ar pattern ("arganomi"), which was observed, was not consistent with the Grenville Front being a crustal-scale southeast-dipping structure. If the structure is further inboard in the Grenville Front tectonic zone, then the asymmetry of "arganomi" is not necessarily inconsistent, since the Grenville Front is not the major crustal structure responsible for generating the "argonami".

SUGGESTIONS FOR FURTHER INVESTIGATIONS

Many aspects of the geology, metamorphism, structure, geochemistry and geochronology of the Timmins Creek area have been examined in this study. Despite addressing many of the questions noted at the beginning of this study, several new questions have arisen as a result of this research project.

- Do the migmatitic gneisses in Street Township represent part of an overriding transported thrust sheet?
- Does the synform in Domain 2 represent a complimentary structure immediately north of the hanging-wall antiform?
- Do the enclaves of Domain 4 represent an exposure of lower crust sheet in Street Township?
- As discussed, the proposed tectonic model for the Timmins Creek area may have application with respect to regional-scale tectonic and metamorphic questions along the Grenville Front and Grenville Front tectonic zone from Ontario to Labrador. This approach needs to be tested elsewhere along the Grenville Front to determine if this model can be applied regionally.
- The significance of the atypical REE pattern of part of the Mississagi quartzite should be investigated at a more regional scale within the Southern Province. Is it an important stratigraphic marker horizon?
- Additional geochronology is needed in the Grenville Front tectonic zone east of Sudbury to address some of the above questions and to confirm the presence of Nipissing gabbro age rocks in the Grenville Front tectonic zone, as well as the distribution of metamorphic effects at 1.7 and 1.45 Ma within the Grenville Front tectonic zone.

References

Ayres, L.D., Lumbers, S.B., Milne, V.G. and Robeson, D.W. 1971. Southern sheet, Ontario Geological Map, Ontario Department of Mines and Northern Affairs, Map 2197, scale 1:1 013 760.

Beaumont, C., Fullsack, P., Hamilton, J. and Willett, S.D. 1992. Preliminary results from a mechanical model of the tectonics of compressive crustal deformation; *in* Alberta Basement Transect, Lithoprobe Report 28, p.22-61.

Bennett, G., Dressler, B.O. and Robertson, J.A. 1991. The Huronian Supergroup and associated intrusive rocks; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.549-591.

Berman, R.G. 1991. Thermobarometry using multi-equilibrium calculations: a new technique with petrological applications; The Canadian Mineralogist, v.29, p.833-855.

Bethune, K.M. 1997. The Sudbury dyke swarm and its bearing on the tectonic development of the Grenville Front, Ontario, Canada; Precambrian Research, v.85, p.117-146.

Bethune, K.M. and Davidson, A. 1997. Grenvillian metamorphism of the Sudbury diabase dyke-swarm: from protolith to two-pyroxene-garnet coronite; The Canadian Mineralogist, v.35, p.1191-1220.

Blonde, J.A. 1996. Petrology and metamorphism of Nipissing diabase of May Township, Ontario; unpublished MSc thesis, Carleton University, Ottawa, Ontario, 160p.

Brown, J.M. 1968. Structure and origin of the Grenville front south of Coniston, Ontario; unpublished PhD thesis, University of Wisconsin, Madison, Wisconsin, 168p.

Bucher, K. and Frey, M. 1994. Petrogenesis of metamorphic rocks; 6th Edition. Springer-Verlag, New York, 318p.

Buckley, S.B., Easton, R.M., Ford, F.D. and Lobanok, L. 1997. Analysis of *P–T* conditions along the Grenville Front east of Sudbury, Ontario; Geological Association of Canada, Program with Abstracts, v.22, p.A-20.

Bullock, W.R. 1987. A geochronological study of the Grenville Front near Coniston, Ontario, Canada; unpublished MSc thesis, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, 47p.

Card, K.D. 1964. Metamorphism in the Agnew Lake area, Sudbury District, Ontario, Canada; Geological Society of America Bulletin, v.75, p.1011-1030.

——— 1968. Economic geology of the Espanola–Whitefish Falls area, District of Sudbury, Ontario; Ontario Division of Mines, Open File Report 5017, 29p.

——— 1978. Metamorphism of the Middle Precambrian (Aphebian) rocks of the eastern Southern Province; *in* Metamorphism in the Canadian Shield, Geological Survey of Canada, Paper 78-10, p.269-282.

——— 1992. Circa 1.75 Ga ages for plutonic rocks from the Southern Province and adjacent Grenville Province: what is the expression of the Penokean orogeny?: Discussion; *in* Radiogenic Age and Isotopic Studies: Report 6; Geological Survey of Canada, Paper 92-2, p.227-228.

Card, K.D. and Hutchinson, R.W. 1972. The Sudbury Structure. Its regional geological setting; *in* Geological Association of Canada, Special Paper 10, p.67-78.

Card, K.D., Innes, D.G. and Debicki, R.L. 1977. Stratigraphy, sedimentology, and petrology of the Huronian Supergroup in the Sudbury–Espanola area; Ontario Division of Mines, Geoscience Study 16, 99p.

Card, K.D. and Jackson, S.J. 1995. Tectonics and metallogeny of the Early Proterozoic Huronian foldbelt and the Sudbury Structure of the Canadian Shield, Field Trip Guidebook; Geological Survey of Canada, Open File 3139, 55p.

Carmichael, D.M. 1978. Metamorphic bathozones and bathograds: a measure of the depth of post-metamorphic uplift and erosion of regional scale; American Journal of Science, v.278, p.769-797.

Chen,Y.D., Krogh, T.E. and Lumbers, S.B. 1995. Neoarchean trondhjemitic and tonalitic orthogneiss identified within the northern Grenville Province in Ontario by precise U-Pb dating and petrologic studies; Precambrian Research, v.72, p.263-281.

Collins, W.H. 1913. Geology of a portion of Sudbury map area, south of Lake Wanapitei, Ontario; Geological Survey of Canada, Summary Report for 1913.

Cooke, H.C. 1946. Problems of Sudbury geology; Geological Survey of Canada, Bulletin 3, 77p.

Corfu, F. and Andrews, A.J. 1986. A U-Pb age for mineralized Nipissing diabase, Gowganda, Ontario; Canadian Journal of Earth Sciences, v.23, p.107-109.

Corfu, F. and Easton, R.M. 1998. Extension of the Huronian magmatic suite inside the Grenville Province: new zircon U-Pb evidence from the Grenville Front tectonic zone in Street Township, Sudbury region, Ontario; 44th Annual Institute on Lake Superior Geology, Proceedings, v.44, pt.1, p.59-60.

——— in press. U-Pb evidence for polymetamorphic history of Huronian rocks in the Grenville Front tectonic zone east of Sudbury, Ontario; Chemical Geology.

Corfu, F., Easton, R.M. and Murphy, E. 1998. Zircon, monazite and titanite U-Pb isotopic systematics in polymetamorphic rocks of the Grenville Front tectonic zone near Sudbury, Ontario; Geological Society of America, Abstracts with Program, v.30, no.6, p.A-215.

Craigie, E.R. 1976. Diamond drill records, Gulf Mineral Company, Street Township; Assesment Files, Sudbury Resident Geologist's Office, Ministry of Northern Development and Mines, File #SP010, 14p.

Cumming, G.L., Wilson, J.T., Farquhar, R.M. and Russell, R.D. 1955. Some dates and subdivisions of the Canadian Shield; Geological Association of Canada, Proceedings, v.7, pt.2, p.27-79.

Dalziel, I.W.D., Brown, J.M., and Warren, T.E. 1969. The structural and metamorphic history of the rocks adjacent to the Grenville Front near Sudbury, Ontario, and Mount Wright, Quebec; *in* Age relations in high-grade metamorphic terrains. Geological Association of Canada, Special Paper 5, p.207-224.

Davidson, A. 1991. Metamorphism and tectonic setting of gabbroic and related rocks in the Central Gneiss Belt, Grenville Province Ontario; Geological Association of Canada, Toronto '91, Guidebook, Field Trip A2, 60p.

——— 1992. Relationship between faults in the Southern Province and the Grenville Front southeast of Sudbury, Ontario; *in* Current Research, Part C, Geological Survey of Canada, Paper 92-1C, p.121-127.

——— 1994. Grenville Front relationships in the Sudbury area, Ontario; Geological Association of Canada, Field Trip B2, Guidebook.

——— 1997. New developments in Grenville Front geology, Sudbury area, Ontario; Institute on Lake Superior Geology, Field Trip Guidebook, v.43, pt.3, 38p.

——— 1998. Questions of correlation across the Grenville Front east of Sudbury, Ontario; *in* Current Research 1998-C; Geological Survey of Canada, Paper 98-1C, p.145-154.

Davidson, A., and Ketchum, J.W.F. 1993. Grenville Front studies in the Sudbury region, Ontario; *in* Current Research, part C; Geological Survey of Canada, Paper 93-1C, p.271-278.

Davidson, A., and van Breemen, O. 1994. U-Pb ages of granites near the Grenville Front, Ontario; *in* Radiogenic Age and Isotopic Studies Report 8; Geological Survey of Canada, Current Research 1994-F, p.107-114.

Davidson, A., van Breemen, O. and Sullivan, R.W. 1992. Circa 1.75 Ga ages for plutonic rocks from the Southern Province and adjacent Grenville Province: what is the expression of the Penokean orogeny?; *in* Radiogenic Age and Isotopic Studies: Report 6; Geological Survey of Canada, Paper 92-2, p.107-118.

Debicki, R.L. 1990. Stratigraphy, paleoenvironment and economic potential of the Huronian Supergroup in the southern Cobalt Embayment; Ontario Geological Survey, Miscellaneous Paper 148, 151p.

Debon, F. and Le Fort, P. 1983. A chemical–mineralogical classification of common plutonic rocks and associations; Transactions of the Royal Society of Edinburgh, Earth Sciences, v.73, p.135-149.

Dickin, A.P. and McNutt, R.H. 1989. Nd model-age mapping of southeastern margin of the Archean foreland in the Grenville Province of Ontario; Geology, v.17, p.299-303.

——— 1990. Nd model-age of mapping on Grenville lithotectonic domains: mid-Proterozoic crustal evolution in Ontario; *in* Mid-Proterozoic Laurentia–Baltica, Geological Association of Canada, Special Paper 38, p.79-94.

Dressler, B.O. 1979. Geology of McNish and Janes townships; Ontario Geological Survey, Report 191, 91p.

——— 1982. Geology of the Wanapitei Lake area; Ontario Geological Survey, Report 213, 131p.

Dressler, B.O., Gupta, V.K. and Muir, T.L. 1991. The Sudbury Structure; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p.593-625.

Easton, R.M. 1992. The Grenville Province; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.713-904.

——— 1996. Geology of garnetiferous gneisses in Street Township, District of Sudbury; *in* Summary of Field Work and Other Activities, 1996, Ontario Geological Survey, Miscellaneous Paper 166, p.70-73.

——— 1999. Platinum group elements, nickel, copper and chromium potential of mafic rocks within the Grenville Front tectonic zone east of Sudbury; *in* Summary of Field Work and Other Activities, 1998, Ontario Geological Survey, Miscellaneous Paper 169, p.195-202.

Easton, R.M., Buckley, S.G., Lobanok, E. and James, R.S. 1996. Grenville–Southern province relationships in Street Township, District of Sudbury; *in* Summary of Field Work and Other Activities 1996, Ontario Geological Survey, Miscellaneous Paper 166, p.66-69.

Easton, R.M. and James, R.S. 1997a. Revisiting the disappearance of the Huronian in the Sudbury–Crerar area: part 1. The amphibolite story; Geological Association of Canada, Program with Abstracts, v.22, p.A43.

——— 1997b. Revisiting the disappearance of the Huronian in the Sudbury–Crerar area: part 2. The paragneiss story; Geological Association of Canada, Program with Abstracts, v.22, p.A44.

——— 1997c. Revisiting the disappearance of the Huronian in the Sudbury–Crerar area: insights from the geochemistry of amphibolites and paragneisses; 43rd Institute on Lake Superior Geology, Proceedings, v.43, pt.1, p.19-20.

Easton, R.M. and Murphy, E. 2000. Precambrian geology of Street Township; Ontario Geological Survey, Preliminary Map P.3427, scale 1:20 000.

——— in press. Precambrian geology of Street Township, District of Sudbury; Ontario Geological Survey, Open File Report.

Fairbairn, H.W. 1939. Geology of the Ashigami Lake area; Ontario Department of Mines, Volume 48, 1939, accompanied by Map 48m (Ashigami Lake area).

Fairbairn, H.W., Hurley, P.M., Card, K.D. and Knight, C.J. 1969. Correlation of radiometric ages of Nipissing diabase and Huronian metasediments with Proterozoic orogenic events in Ontario; Canadian Journal of Earth Science, v.6, p.489-497.

Fedo, C.M., Young, G.M. and Nesbitt, H.W. 1997b. Paleoclimatic control on the composition of the Paleoproterozoic Serpent Formation, Huronian Supergroup, Canada: a greehouse to icehouse transition; Precambrian Research, v.86, p.201-223.

Fedo, C.M., Young, G.M., Nesbitt, H.W. and Hanchar, J.M. 1997a. Potassic and sodic metasomatism in the Southern Province of the Canadian Shield: evidence from the Paleoproterozoic Serpent Formation, Huronian Supergroup, Canada; Precambrian Research, v.84, p.17-36.

Fox, J.S. 1971. Co-existing chloritoid and staurolite and the staurolite-chloritoid isograd from the Agnew Lake area, Ontario, Canada; Geological Magazine, v.108, p.205-219.

Fralick, P.W. and Miall, A.D. 1989. Sedimentology of the Lower Huronian Supergroup (Early Proterozoic), Elliot Lake area, Ontario, Canada; Sedimentary Geology, v.63, p.127-153.

Fueten, F. and Redmond, D.J. 1992. Structural studies in the Southern Province, south of Sudbury, Ontario; *in* Current Research; Geological Survey of Canada, Paper 92-1C, p.179-187.

——— 1997. Documentation of a 1450 Ma contractional orogeny preserved between the 1850 Ma Sudbury impact structure and the 1 Ga Grenville orogenic front, Ontario; Geological Society of America Bulletin, v.109, p.268-279.

Fyon, A.J., Bennett, G.L., Jackson, S., Garland, M.I. and Easton, R.M. 1992. Metallogeny of the Proterozoic Eon; *in* Geology of Ontario, Chapter 23, Ontario Geological Survey, Special Volume 4, Part 2, p.1177-1215.

Fyon, A.J., Jackson, S.L., Lightfoot, P.C., Meyer, W., Bennett, G.L., Reland, J. and Lavigne, M.J. 1995. Metallogeny of the Proterozoic eon, Southern Province, Ontario; The Canadian Mineralogist, v.33, p.941-942.

Gates, B.I. 1991. Sudbury mineral occurrence study; Ontario Geological Survey, Open File Report 5771, 235p.

Gibbs, J.W. 1961. The scientific papers of J. Willard Gibbs. Volume One. Thermodynamics. Dover Publications, New York.

Gordon, T.M. 1996. Generalized thermobarometry: WEBINVEQ with the TWQ 1.02 data base; The World Wide Web, http://ichor.geo.ucalgary.ca/~tmg/Webinveg/rgb95.html.

Grant, J.A., Pearson, W.J., Phemister, T.C. and Thomson, J.E. 1962. Broder, Dill, Neelon, and Dryden townships, Ontario Department of Mines, Geological Report 9, p.1-24.

Green, A.G., Milkereit, B., Davidson, A., Spenser, C., Hutchinson, D.R., Cannon, W.F., Lee, M.W., Agena, W.F., Behrendt, J.C. and Hinze, W.J. 1988. Crustal structure of the Grenville Front and adjacent terranes; Geology, v.16, p.788-792.

Haggart, M.J., Jamieson, R.A., Reynolds, P.H., Krogh, T.E., Beaumont, C. and Culshaw, N.G. 1993. Last gasp of the Grenville orogeny: thermochronology of the Grenville Front tectonic zone near Killarney, Ontario; Journal of Geology, v.101, p.575-589.

Heaman, L.M. 1995. U-Pb dating of mafic rocks: past, present and future; Geological Association of Canada, Program with Abstracts, v.20, p.A-43.

——— 1997. Global mafic magmatism at 2.45 Ga: remnants of an ancient large igneous province?; Geology, v.25, p.299-302.

Hubbard, L. 1998. A petrographic study of Proterozoic meta-pyroxenites of the Grenville Front tectonic zone, Sudbury, Ontario; unpublished BSc thesis, Laurentian University, Sudbury, Ontario, 48p.

Hodges, K.V. and Spear, F.S. 1982. Geothermometry, geobarometry and the new Al_2SiO_5 triple point at Mt. Mooilauke, New Hampshire; American Mineralogist, v.67, p.1118-1134.

Holland, T. and Blundy, J. 1994. Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry; Contributions to Mineralogy and Petrology, v.116, p.433-447.

Hoffman, P.F. 1989. Precambrian geology and tectonic history of North America; *in* The Geology of North America—an overview; Geological Society of America, The Geology of North America, Volume A, p.447-512.

Innes, D.G. 1972. Proterozoic volcanism and associated sulphide-bearing metasediments in the Sudbury area, Ontario; unpublished BSc thesis, Laurentian University, Sudbury, Ontario.

——— 1977. Proterozoic volcanism in the Southern Province of the Canadian Shield; unpublished MSc thesis, Laurentian University, Sudbury, Ontario, 161p.

Irvine, T.N. and Barager, W.R.A. 1971. A guide to chemical classification of the common volcanic rocks; Canadian Journal of Earth Sciences, v.8, p.523-548.

Jamieson, R.A. and Beaumont, C. 1989. Deformation and metamorphism in convergent orogens: a model for uplift and exhumation of metamorphic terrains; *in* Evolution of Metamorphic Belts, Geological Society, Special Publication No. 43, p.117-129.

Jamieson, R.A., Culshaw, N.G. and Corrigan, D. 1995. Northwest propagation of the Grenville Orogen: Grenvillian structure and metamorphism near Key Harbour, Georgian Bay, Ontario, Canada; Journal Metamorphic Geology, v.13, p.185-207.

Jensen, L.S. 1976. A new cation plot for classifying subalkalic volcanic rocks; Ontario Division of Mines, Miscellaneous Paper 66, 22p.

Jolly, W.T. 1987. Lithophile elements in Huronian low-Ti continental tholeiites from Canada, and evolution of the Precambrian mantle; Earth and Planetary Science Letters, v.85, p.401-415.

Johns, G.W. 1996. Precambrian geology of Garson and Blezard townships; Ontario Geological Survey, Open File Report 5950, 47p.

Junnila, R.M. and Young, G.M. 1995. The Paleoproterozoic upper Gowganda Formation, Whitefish Falls area, Ontario, Canada: subaqueous deposits of a braid delta; Canadian Journal of Earth Sciences, v.32, p.197-209.

Keays, R.R., Vogel, D.C., James, R.S., Peck, D.C., Lightfoot, P.C. and Prevec, S.A. 1995. Metallogenic potential of the Huronian–Nipissing magmatic province; *in* The Northern Margin of the Southern Province of the Canadian Shield, The Canadian Mineralogist, v.33, p.932-933.

Kerrick, D.M. ed. 1990. The Al_2SiO_5 polymorphs; Reviews of Mineralogy, v.22, 406p.

Ketchum, J.W.F., Jamieson, R.A., Heaman, L.M., Culshaw, N.G. and Krogh, T.E. 1994. 1.45 Ga granulites in the southwestern Grenville Province: geologic setting, *P–T* conditions, and U-Pb geochronology; Geology, v.22, p.215-218.

Krogh, T.E. 1994. Precise U-Pb ages for Grenvillian and pre-Grenvillian thrusting of Proterozoic and Archean metamorphic assemblages in the Grenville Front tectonic zone, Canada; Tectonics, v.13, p.963-982.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S.L., Machado, N., Greenough, J.D. and Nakamura, E. 1988. Precise U-Pb isotopic ages of diabase dykess and mafic to ultramafic rocks using trace amounts of baddeleyite and zircon; *in* Mafic Dyke Swarms, Geological Association of Canada Special Paper 34, p.147-152.

Krogh, T.E., Davis, D.W. and Corfu, F. 1984. Precise U-Pb zircon and baddelyite ages for the Sudbury Structure; *in* Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.431-446.

Krogh, T.E., Kamo, S.L. and Bohor, B.F. 1996. Shock metamorphosed zircons with correlated U-Pb discpordance and melt rocks with concordant protolith ages indicate an impact origin for the Sudbury Structure; *in* Earth Processes: Reading the Isotopic Code; American Geophysical Union, Geophysical Monograph 95, p.343-353.

Kwak, T.A.P. 1968. Metamorphic petrology and geochemistry across the Grenville Province, Southern Province boundary, Dill Township, Sudbury, Ontario; unpublished PhD thesis, McMaster University, Hamilton, Ontario, 200p.

——— 1971. Justification for both ionic and thermal reactions in Grenville Province pelitic rocks near Sudbury, Ontario, Canada; Canadian Journal of Earth Sciences, v.8, p.1333-1354.

La Tour, T.E. 1979. The nature and origin of the Grenville Front near Coniston, Ontario: a reinterpretation; unpublished PhD thesis, University of Western Ontario, London, Ontario, 344p.

——— 1981. Metamorphism and geothermometry near Coniston, Ontario: a clue to the tectonic evolution of the Grenville Front; Canadian Journal of Earth Sciences, v.18, p.884-898.

La Tour, T.E. and Fullagar, P.F. 1986. Rb/Sr study of mylonitic rocks at the Grenville Front near Coniston, Ontario: some preliminary results; *in* The Grenville Province, Geological Association of Canada, Special Paper 31, p.223-233.

Leake, B.E. and 21 others. 1997. Nomenclature of amphiboles: report of subcommittee on amphiboles of the International Mineralogical Association, commission on new minerals and mineral names; The Canadian Mineralogist, v.35, p.219-246.

Lesher, C.M., Goodwin, A.M., Campbell, I.H. and Gorton, M.P. 1986. Trace-element geochemistry of ore-associated and barren, felsic metavolcanic rocks in the Superior Province, Canada; Canadian Journal of Earth Sciences, v.23, p.222-237.

Lightfoot, P.C. and Naldrett, A.J. 1996. Petrology and geochemistry of the Nipissing gabbro: exploration strategies for nickel, copper, and platinum group elements in a large igneous province; Ontario Geological Survey, Study 58, 81p.

Lumbers, S.B. 1971. Some aspects of the northwestern margin of the Grenville Province between Sudbury and Lake Timiskaming, Ontario; *in* Abstracts; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Sudbury, Ontario, May 13-15, 1971, p.36-37.

——— 1973. River Valley area; Ontario Division of Mines, Preliminary Map P.844, scale 1:63 360.

——— 1975. Geology of the Burwash area, District of Nipissing, Parry Sound and Sudbury , Ontario; Ontario Division of Mines, Geological Report 16, 158p.

——— 1978. Geology of the Grenville Front tectonic zone in Ontario; *in* Toronto '78, Field Trip Guidebook, Geological Society of America, p.347-361.

Maniar, P.D. and Piccoli, P.M. 1989. Tectonic discrimination of granitoids; Geological Society of America Bulletin, v.101, p.635-643.

McLennan, S.M., Fryer, B.J. and Young, G.M. 1979. The geochemistry of the carbonate-rich Espanola Formation (Huronian) with emphasis on the rare earth elements; Canadian Journal of Earth Sciences, v.16, p.230-239.

Meldrum, A., Abdel-Rahman, A.-F.M., Martin, R.F. and Wodicka, N. 1997. The nature, age and petrogenesis of the Cartier Batholith, northern flank of the Sudbury Structure, Ontario, Canada; Precambrian Research, v.82, p.265-285.

Meyer, W., Jerome, L.B., Gates, B.I. and Lacey, L.K. 1990. Sudbury Resident Geologist's area 1989; *in* Report of Activities, 1989, Regional and Resident Geologists, Ontario Geological Survey, Miscellanenous Paper 147, p.299-309.

Miyashiro, A. 1961. Evolution of metamorphic belts; Journal of Petrology, v.2, p.277-311.

———. 1973. Paired and unpaired metamorphic belts; Tectonophysics, v.17, p.241-254.

Murphy, E.I., James, R.S. and Easton, R.M. 1998. Revisiting the position of the Grenville Front in the Timmins Creek area, Sudbury, Ontario; Geological Society of America, Abstracts with Program, v.30, no.6, p.A-95.

——— 1999. Geology and metamorphic history of the Timmins Creek area, Grenville Front tectonic zone, Sudbury, Ontario; Geological Association of Canada, Program with Abstracts, v.24,p.89.

Naldrett, A.J. 1984. Summary, discussion, and synthesis; *in* The Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.533-570.

Nesbitt, H.W. and Young, G.M. 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites; Nature, v.299, p.715-717.

Noble, S.R. and Lightfoot, P.C. 1992. U-Pb baddeleyite ages of the Kerns and Triangle Mountain intrusions, Nipissing diabase, Ontario; Canadian Journal of Earth Sciences, v.29, p.1424-1429.

Parker, J.R. and Ayer, J.A. 1997. Distribution of evolved rhyolites in the Superior Province, Ontario; *in* Summary of Field Work and Other Activities, Ontario Geological Survey, Miscellaneous Paper 168, p.59-62.

Pearce, J.A. and Cann, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses; Earth Planetary Science Letters, v.19, p.290-300.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks; Journal of Petrology, v.25, p.956-983.

Pearson, W.J. 1959. Origin of the kyanite occurrences in the Wanapitei and Crocan Lake areas of Ontario; unpublished PhD thesis, Queen's University, Kingston, Ontario, 336p.

——— 1962. Kyanite occurrences in Dryden Township. Ontario Department of Mines, Geological Report 9, p.25-37.

Peck, D.C., James, R.S. and Chubb, P. 1993. Geological environments for PGE-Cu-Ni mineralization in the East Bull Lake gabbro-anorthosite intrusion, Ontario; Exploration and Mining Geology, v.2, p.85-104.

Peck, D.C., James, R.S., Chubb, P.T., Prevec, S.A. and Keays, R.R. 1995. Geology, metallogeny and petrogenensis of the East Bull Lake intrusion, Ontario; Ontario Geological Survey, Open File Report 5923, 117p.

Phemister, T.C. 1961. The boundary between the Timiskaming and Grenville sub-provinces in the townships of Neelon, Dryden, Dill and Broder, District of Sudbury; Ontario Department of Mines, Preliminary Report 1961-5, 61p.

Prevec, S.A. 1993. An isotopic, geochemical and petrographic investigation of the genesis of early Proterozoic mafic intrusions and associated volcanics near Sudbury, Ontario; unpublished PhD thesis, University of Alberta, Edmonton, Alberta, 223p.

Pye, E.G., Naldrett, A.J. and Giblin, P.E. eds. 1984. Geology and ore deposits of the Sudbury Structure; Ontario Geological Survey, Special Volume 1, 603p.

Quirke, T.T. and Collins, W.H. 1930. The disappearance of the Huronian; Geological Survey of Canada, Memoir 160, 129p.

Riller, U., Schwerdtner, W.M., Halls, H.C. and Card, K.D. 1999. Transpressive tectonism in the eastern Penokian orogen, Canada: consequences for Proterozoic crustal kinematics and continental fragmentation; Precambrian Research, v.93. p.51-70.

Rivers, T., van Gool, J.A.M. and Connelly, J.N. 1993. Contrasting tectonic styles in the northern Grenville Province: implication for the dynamics of orogenic fronts; Geology, v. 1, p. 127-1130.

Rousell, D.H. 1984. Structural geology of the Sudbury Basin; *in* The Geology and Ore Deposits of the Sudbury Structure, Ontario Geological Survey, Special Volume 1, p.83-95.

Schandal, E.S., Gorton, M.P. and Davis, D.W. 1994. Albitization at 1700 ± 2 Ma in the Sudbury–Wanapitei Lake area, Ontario; Canadian Journal of Earth Sciences, v.31, p.597-607.

Sims, P.K., Card, K.D. and Lumbers, S.B. 1981. Evolution of Early Proterozoic Bbsins of Canada; *in* Proterozoic Basins of Canada, Geological Survey of Canada, Paper, 81-10, p.379-397.

Smith, P.E., York, D., Easton, R.M., Ozdemir, O. and Layer, P.W. 1994. A laser $^{40}Ar/^{39}Ar$ study of minerals across the Grenville Front: investigation of reproducible excess Ar patterns; Canadian Journal of Earth Sciences, v.31, p.808-817.

Spear, F.S. 1993. Metamorphic phase equilibria and pressure–temperature–time paths; Mineralogical Society of America, Washington, D.C., 799p.

Stockwell, C.H. 1964. Fourth report on structural provinces, orogenies, and time classification of rocks of the Canadian Precambrian Shield; Geological Survey of Canada, Paper 64-17, pt.II, 21p.

Streckeisen, A. 1976. To each plutonic rock its proper name; Earth-Science Reviews, v.12, p.1-33.

Sullivan, R.W. and Davidson, A. 1993. Monazite age of 1747 Ma confirms post-Penokean age for the Eden Lake complex, Southern Province; *in* Radiogenic Age and Isotopic Studies: Report 7; Geological Survey of Canada, Paper 93-2, p.45-48.

Taylor, S.R. and McLennan, S.M. 1985. The continental crust: its composition and evolution, Blackwell, Oxford, 312p.

Thomson, J.E. 1960. Uranium and thorium deposits at the base of the Huronian System in the District of Sudbury; Ontario Department of Mines, Geological Report 1, 40p.

Thomson, J.E. and Card, K.D. 1963. Kelly and Davis townships, Ontario Department of Mines, Geological Report 15, 20p.

Tomlinson, K.Y. 1996. The geochemistry and tectonic setting of Early Precambrian greenstone belts, northern Ontario, Canada; unpublished PhD thesis, University of Portsmouth, Portsmouth, U.K., 287p.

Van Schmus, W.R. 1976. Early and Middle Proterozoic history of the Great Lakes area, North America; Royal Society, Philosophical Transcations, v.A280, p.605-628.

Vogel, D.C. 1996. The geology and geochemistry of the Agnew intrusion: implications for the petrogenesis of early Huronian mafic igneous rocks in central Ontario, Canada; unpublished PhD thesis, University of Melbourne, Australia, 292 p.

Wager, T.E. 1960. The major element variation of the layered series of the Skaergaard intrusion. Journal of Petrology, v.1, p.364-398.

Walker, K.R. 1969. The Palisades sill, New Jersey: a reinvestigation; Geological Society of America, Special Paper 111, 178p.

Willett, S.D., Beaumont, C. and Fullsack, P. 1993. Mechanical model for the tectonics of doubly vergent compressional orogens; Geology, v.21, p.371-374.

Winardhi, S. and Mereu, R.F. 1997. Crustal velocity structure of the Superior and Grenville provinces of the southeastern Canadian Shield; Canadian Journal of Earth Sciences, v.34, p.1167-1183.

Winchester, J.A. and Floyd, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements; Chemical Geology, v.20, p.325-343.

Winkler, H.G.F. 1967. Petrogenesis of metamorphic rocks; Springer-Verlag, New York, Second Edition, 237p.

Wodicka, N. and Card, K.D. 1995. Late Archean history of the Levack gneiss complex, southern Superior Province, Sudbury, Ontario: new evidence from U-Pb geochronology; Precambrian '95, Program with Abstracts, p.191.

Wood, D.A. 1980. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province; Earth and Planetary Science Letters, v.50, p.11-30.

Wu, J., Milkereit, B. and Boerner, D.E. 1995. Seismic imaging of the enigmatic Sudbury Structure; Journal of Geophysical Research, v.100, p.4117-4130.

Wynne-Edwards, H.R. 1972. The Grenville Province; *in* Variations in Tectonic Styles in Canada, Geological Association of Canada, Special Paper 11, p.263-334.

Young, G.M. 1983. Tectono-sedimentary history of early Proterozoic rocks of the northern Great Lakes area; *in* Early Proterozoic Geology of the Great Lakes Region; Geological Society of America, Memoir 160, p.15-32.

Zolnai, A.I., Price, R.A. and Helmstaedt, H. 1984. Regional cross section of the Southern Province adjacent to Lake Huron, Ontario: implication for tectonic significance of the Murray Fault Zone; Canadian Journal of Earth Sciences, v.21, p.447-456.

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.

MAPS NOT FILMED

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